GEOPHYSICS

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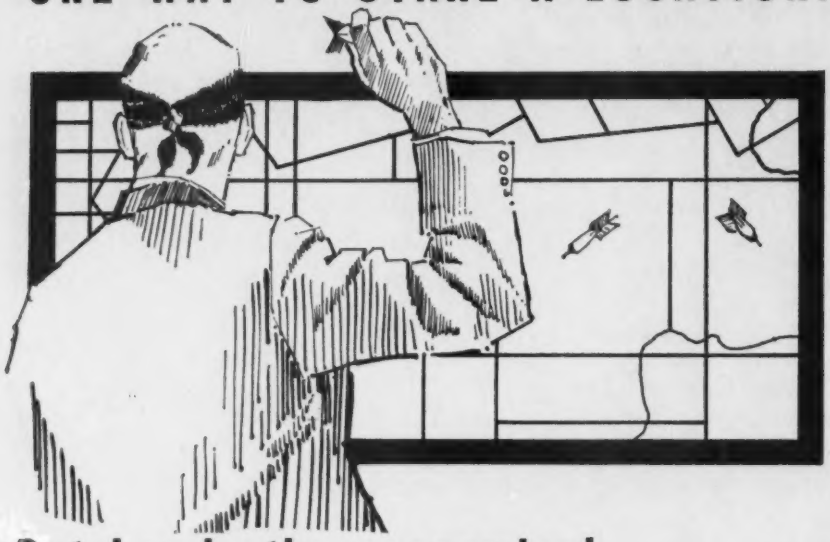

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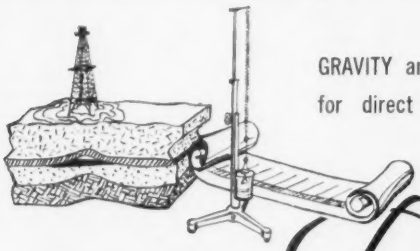

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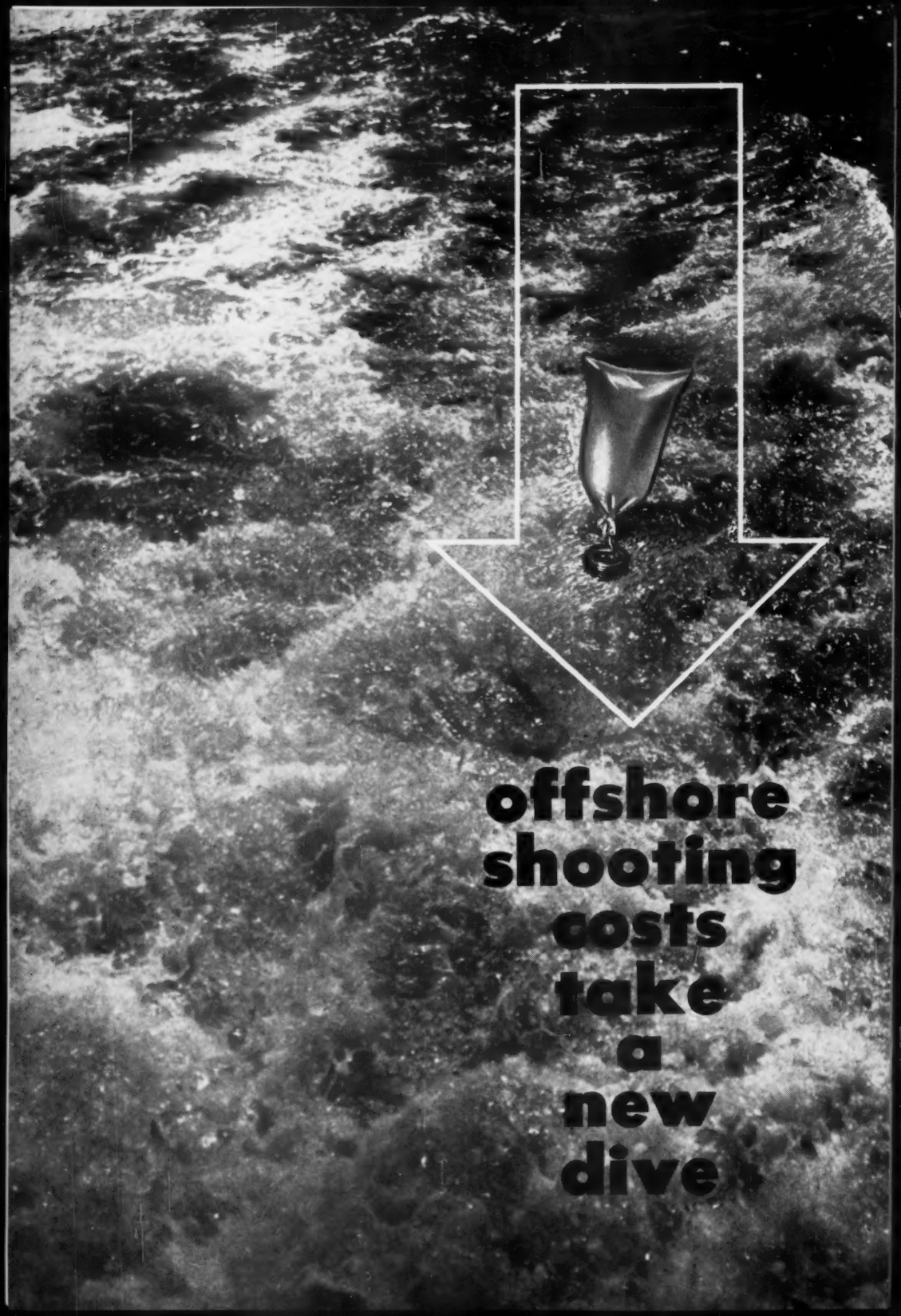
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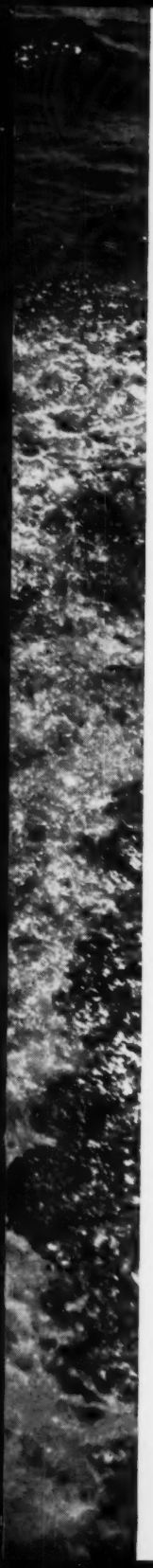

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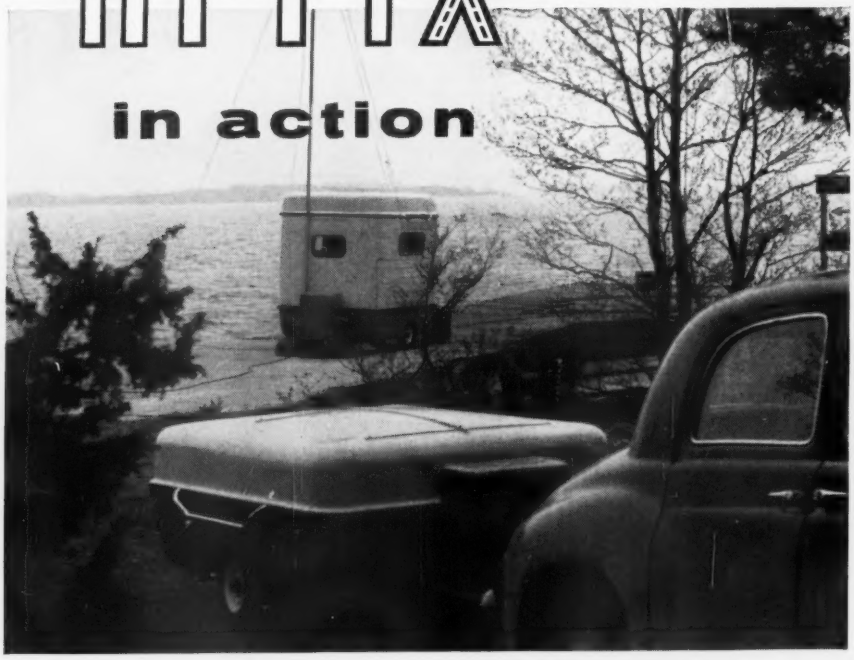

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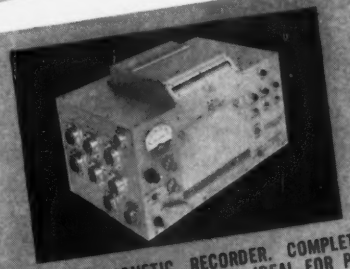

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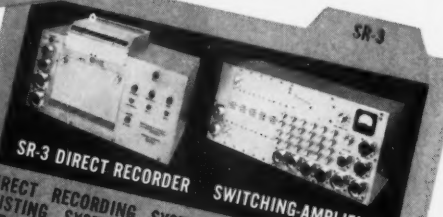

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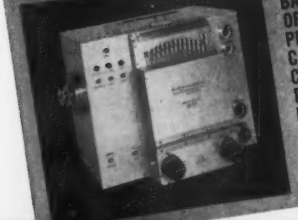

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Volume XXVI JUNE, 1961 Number 3

GEOPHYSICS

MOTION OF THE GROUND ON ARRIVAL OF REFLECTED LONGITUDINAL AND TRANSVERSE WAVES AT WIDE-ANGLE REFLECTION DISTANCES*

T. C. RICHARDS†

Abstract: The horizontal and vertical motions of the surface of the ground on the arrival of reflected longitudinal and transverse waves from an elastic discontinuity are determined theoretically, with special reference to those parameters encountered in exploring for limestone structures in the foothills of Western Canada by wide-angle reflection techniques. The results, which cover a wide range of possible overburden velocities, are expressed by means of curves from which the displacement for any practical elastic contrast, depth and observation distance may be readily determined. Properties of these curves are examined empirically. The theory assumes plane waves in determining the amplitude ratios at the structural or free surface discontinuities and spherical waves in deriving spread factors. Corrections to the curves on account of a non-uniform overburden velocity are considered in the case of a typical central foothills well. The evidence for *PP* and *PS* in model, and to a less extent in field work and the significance of phase changes on reflection are discussed. It is concluded that the horizontal geophone should prove to be a useful additional tool in wide-angle reflection surveys in disturbed foothills zones. Here, it could confirm or refute the arrival of a reflection registered by the vertical geophones in the many cases where doubt exists.

INTRODUCTION

In seismic exploration for buried structures, geophones measuring the vertical amplitude of the ground movement from an explosion are almost exclusively used. This is because by far the greater part of seismic work is confined to longitudinal (*P*) reflections at very small angles of incidence, while in the case of refractions, it is usually maintained that even if the critical angle is large, the low velocity of the near surface unconsolidated layers is such as to bend the path of refraction towards the vertical at the geophone.

There have been instances when horizontal motion has been recorded, and Ricker and Lynn (1950) show how such motion is caused by the arrival of a transverse (*SV*) wave (hereinafter referred to as the *S* wave), which had been derived on reflection at the base of unconsolidated material from the incident *P* wave. They also point out that the horizontal motion of this wave is greatly increased at a critical distance, the motion gradually decreasing for greater distances. Other workers such as White, Heaps and Lawrence (1956) and Jolly (1956) have used horizontal geophones in their investigations of the motion from shear sources.

In foothills country, where reasonably high velocity rocks outcrop and weathering is negligible, a *P* wave refracted at the critical angle from an elastic interface may give rise to a strong horizontal component of ground motion, and this could apply also to wide-angle reflections, the vertical displacements of which are used in mapping foothills structures as discussed by Richards (1960). Strong horizontal motion in a refracted wave at the surface was recorded by the author many years ago in the S.W. Iranian foothills; here, using low frequency horizontal and vertical mechanical seismographs, the amplitudes of the first refracted motion on each record were practically identical.

There seems to be, therefore, a good case for extended experiments using horizontal geophones, at refraction or wide-angle reflection distances,

* Manuscript received by the Editor May 24, 1960.

† British Petroleum Co., Ltd., London, England.

especially in foothills country. This paper, however, will mainly be devoted to the determination of the theoretical vertical and horizontal displacement amplitudes to be expected at a free surface from the reflection of P waves at elastic interfaces, either as P or S waves; the elastic parameters will be largely those encountered in petroleum exploration. For simplicity, the solution will be found for a uniform overburden but the effects caused by departures from this idealized condition will be examined.

ELASTIC PARAMETERS IN EXPLORATION

In the seismic exploration of Palaeozoic limestone structures in Western Canada, the average velocity of the overlying sediments, consisting mainly of sands, sandstones, shales, varies approximately from about 10,000 ft/sec to 14,000 ft/sec in accordance with the lithology and degree of consolidation of the rocks. If the rocks are calcareous, as is the case in the thick Triassic deposits of the Western Canadian foothills, immediately in front of the Rocky Mountains, the effective overburden velocity may be as much as 16,000 ft/sec. It becomes of interest, therefore, to investigate the motion of the surface of the earth under differing overburden velocities, taking 20,000 ft/sec as the effective velocity in the limestone structure. Density is a function of consolidation or compaction and of the nature of the inter-granular material. In a general way, we may say that an increase in density is accompanied by an increase in velocity. At a velocity of 10,000 ft/sec, we assign a density of 2.2 gr/cc and at 20,000 ft/sec, a density of 2.65 gr/cc, which refers approximately to maximum compaction of siliceous and limestone rocks. Densities at intermediate overburden velocities are assumed to fall linearly between the extreme values. Velocities at intervals of 2,000 ft/sec within the practical range together with a high value of 18,000 ft/sec are considered, so that empirical relationships between earth motion and the nature of the overburden may be better examined. In addition, low velocities of 8,270 ft/sec and 6,000 ft/sec are considered but only as far as the first step in the analysis in which the energy distribution of the various wave types at the limestone interface is derived. These low velocities could refer to unconsolidated material whose thickness is not too great; that is, not thick enough to introduce significant increases in compaction, velocity and density.

We have, therefore, the following overburden velocities and densities:

V(ft/sec): 6,000, 8,270, 10,000, 12,000, 14,000, 16,000, 18,000

ρ(gr/cc): 2.02, 2.12, 2.20, 2.29, 2.38, 2.47, 2.56.

If we express the elastic contrast at the interface as the impedance ratio, $r = V\rho/V'\rho'$, we have the following seven values

0.23, 0.33, 0.42, 0.52, 0.63, 0.75, 0.87

and these we shall refer to by letters A to G, respectively.

Throughout, the ratio of the P and S velocities in any one material has been taken to be 2.0 as this appears to be more appropriate for sedimentary rocks than the $\sqrt{3}$ often used in seismological studies of the deeper crustal layers and the earth's mantle. Evidence for this higher ratio may be derived from a paper by Richards (1933) in which the P and S velocities for sediments in S.W. Persia are given. Here, for an overburden consisting of sandstones, marls, anhydrite and salt V_P/V_S, in seven cases, ranges from 1.81 to 2.30 with an average of 2.07; four ratios for limestone range from 1.87 to 2.13 with an average of 1.96.

It is of interest to note, in passing, that with $V_P/V_S = 2$, Poisson's ratio is increased to $\frac{1}{3}$ from the assumed value of $\frac{1}{4}$ for the deeper parts of the earth's crust while the Lamé constants are related by $\lambda = 2\mu$ instead of $\lambda = \mu$.

Exact expressions for the potentials in the various types of waves reflected and refracted at a solid-solid interface from a point compressional source are given by Ewing, Jardetzky and Press (1957), but they are too complex for simple application to the problem in hand. The diffracted energy which necessarily arises with such specialized treatment is of second order compared with that of the conventional reflected and refracted energy. But, provided the depth of the interface is several times the wave length of the incident wave, we may obtain a good approximate solution to the energy partition at the interface by employing plane wave theory; and, to account for the divergence of the wave, a simple spread factor may, thereafter, be applied.

In order to determine the component displace-

ments at the surface of the ground on the arrival of the reflected wave, a third factor must be introduced; this allows for the effect of the wave energy reflected back into the earth. In this regard, the plane wave theory given in the literature will be considered to be appropriate.

Strictly, the attenuation of the wave due to solid friction, viscosity or scattering in a non-uniform earth should also be taken into account. The attenuation factor, however, in reasonably consolidated rocks, is believed to be very small as appeared to be the case in field experiments described by Richards and Walker (1959), and we shall, therefore, omit this factor.

ENERGY DISTRIBUTION AT SOLID-SOLID REFLECTOR

The energy distribution of reflected and refracted plane waves at elastic interfaces was first derived by Knott (1899) while several workers such as Jeffreys (1926), Muskat and Meres (1940), Ergin (1952) and Nafe (1957) have considered aspects of the problem. The subject is discussed generally in Ewing, Jardetzky and Press (1957). Most workers have been concerned with seismological application: Ergin has confined his attention to fluid-solid interfaces, Nafe to solid-solid interfaces with high velocity contrast, while the paper by Muskat and Meres deals only with the problem for angles less than the critical angle of reflection as these authors were concerned with the application of the results to conventional seismic reflection surveys at small angles of incidence.

The analysis, which consists in deriving the ratios of the displacements of PP, PS, PP' and PS' to P from a consideration of the boundary conditions, must satisfy the energy equation

$$c\rho A^2 - c\rho A_1^2 = c'\rho' A'^2 + \gamma\rho B_1^2 + \gamma'\rho' B'^2 \quad (1)$$

or

$$E - E_1 = E' + F_1 + F', \quad (2)$$

where

c, c' = cotangents of the angles of incidence and refraction of the P wave,

γ, γ' = cotangents of the angles of reflection and refraction of the S wave,

A, A_1, A' = amplitudes of displacement potential in P, PP and PP'.

E, E_1, E' = corresponding energies,

B_1, B' = amplitudes of displacement potential in PS and PS',

and

F, F' = corresponding energies.

In solving for the various energy components, some very small and very large arithmetical factors often arise and these must be known fairly accurately. Conventional computing, however, is tedious, but by the application of electronic computing, the desired accuracy is easily achieved with considerable speed. Mr. T. W. Morrison has drawn up a suitable program in the Bendix Intercom 1,000 Double Precision routine, by means of which the machine takes about 75 seconds to record the solutions for ten angles of incidence in any one case, and this time includes the manual time taken in inserting the desired parameters into the program. Angles of incidence have been varied from 0 to 90 degrees at 10-degree intervals, but intervals of 5 degrees and one degree and even a half degree were inserted near critical points. Energy percentages have

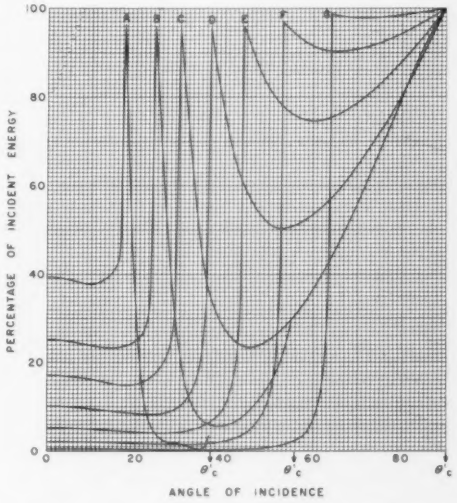

FIG. 1. Percentage of incident energy of P wave reflected as P wave for varying angles of incidence and impedance ratios, r: θ'_c is second critical angle for Cases A, B, and C.

r	0.23,	0.33,	0.42,	0.52,	0.63,	0.75,	0.87
Case	A	B	C	D	E	F	G

been taken to seven decimal points and in all cases the energy equation was satisfied to the sixth point.

Energy Curves

Figures 1, 2 and 3 show curves of the variation of the energy components for the varying impedance ratios. Beyond the critical angle, there is an appreciable transfer of energy at low impedance ratios into PS and PS', but this transfer decreases to zero as the incident angle approaches 90 degrees. In all cases, the energy reflected into PP at the critical angle is greater than 95 percent of the incident energy, but at normal incidence there is a marked falling off from the 39.5 percent for the lowest impedance ratio to 0.5 percent in the case of the highest. Therefore, although a low impedance ratio is an essential condition for good energy return in PP at normal incidence, the converse is true at incidence angles between critical and 90 degrees.

At normal incidence the energy return in PP varies approximately as the square of the impedance difference $\Delta(V\rho)$, as follows from the well-known equation:

$$\frac{E_1}{E} = \left(\frac{V'\rho' - V\rho}{V'\rho' + V\rho}\right)^2, \tag{3}$$

in which the numerator is far more sensitive to impedance change than the denominator. It is interesting to note also that the maximum energy in PS or PS' may be shown to vary approximately as the square of the impedance difference except in Cases A and B, which are seen to be anomalous.

Solutions for Cases A and B are terminated near those incident angles θ_c', which are such as to introduce a second imaginary factor or second critical angle in the analysis. This second critical angle arises when there is no refracted S wave, a condition given when $\sin\theta_c' = V_P/V_{S'}$. In Case A, we find that with an incident P wave at an angle of 36.9 degrees, there is no refracted transverse wave. On approaching this angle, we note curious anomalies in energy distributions of Figures 1, 2 and 3. Case B, whose second critical angle is 55.8 degrees, is also characterized by similar anomalies. There is also an anomalous situation on approaching the second critical angle of 90 degrees for Case C, illustrated especially in Figures 1 and 3.

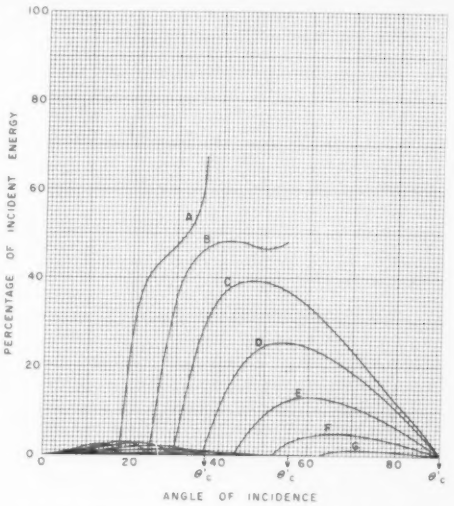

FIG. 2. Percentage of incident energy of P wave reflected as S wave for varying angles of incidence and impedance ratios; θ'_c is second critical angle for Cases A, B, and C.

Similar anomalous conditions are referred to by Ergin (1952) in discussing the energy partition at a water-solid interface. In his studies, however, the ratio of impedances was 0.11 while he considered cases where the ratio of P and S velocities in the solid were 1.6, 1.7 and 1.8, as against our uniform 2.0. Of course, in his work, there is no PS wave but the two critical angles are indicated in his Figure 6, which shows the variation of the square root of the ratio of incident P energy to refracted S energy, with angle of incidence.

It is obvious that in our Cases A and B, the energy in PP beyond the second critical angle must eventually reach 100 percent at grazing incidence while the energy curve for PS must turn over and diminish to zero. In the water-solid case, all the energy goes into PP at the second critical angle.

PHASE CHANGES AT ANGLES GREATER THAN CRITICAL

At the critical angle of reflection for PP defined by $\sin\theta_c = V/V'$, PP' vanishes while as the angle of incidence increases beyond the critical

value, PP, PS and PS' suffer phase changes. This is because A_1/A, B_1/A, B'/A have the form $a+ib$, from which the phase angle, Σ, is given by

$$\tan \sum = \frac{b}{a}.$$

Ewing, Jardetzky and Press (1957) give expressions for the phase angle for the relatively simple cases of liquid-liquid and liquid-solid interfaces under special conditions, but the expression for the solid-solid case is too unwieldy for analytical solution. The electronic computer, however, may be readily applied in individual cases. The interpretation of a phase shift on reflection is to delay the time of arrival of the wave by $\Delta t = \Sigma/\omega$ where ω is the angular frequency. At the critical angle $\Sigma = 0$ and it will reach a value of 180 degrees for reflected P waves for an angle of incidence of 90 degrees.

Mr. Morrison's digital computing program, however, only permitted the determination of phase angle up to an incident angle just less than the second critical angle, for an extension covering greater incidence angles would have involved a complete rewriting of the program; and this

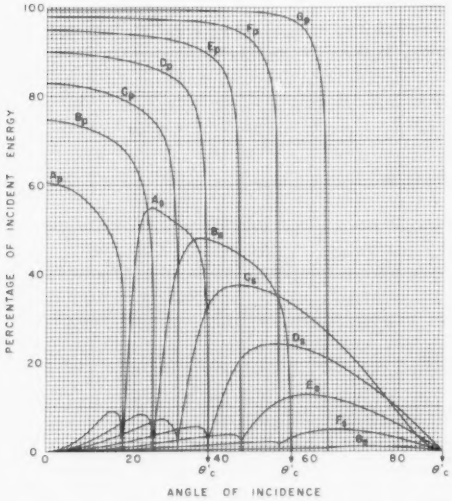

FIG. 3. Percentage of incident energy of P wave refracted as P and S waves for varying angles of incidence and impedance ratios; θ'_c is second critical angle for Cases A, B, and C.

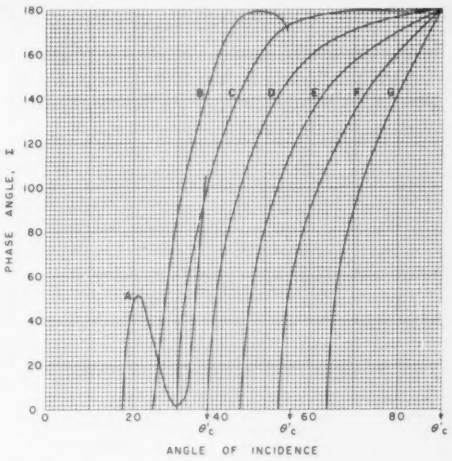

FIG. 4. Phase angle, Σ, of PP wave for varying angles of incidence and impedance ratios.

was not considered necessary at this stage of the investigations. It follows, of course, that the energy evaluations were similarly restricted.

The variations in phase angle of PP with PS with respect to the angle of incidence of the P wave are shown in Figures 4 and 5, respectively. Cases A, B and C for PS show that the phase change exceeds 180 degrees before the second critical angle is reached, Case C reaching 210.7 degrees at $\theta = 89.5$ degrees.

By contrast with PP, it is to be noted that the phase angles for PS at $\theta = 90$ degrees increase with increasing impedance contrast.

THE SPREAD FACTOR

The displacement spread factor in the case of waves reflected without change in type is simply given by the inverse of the total distance travelled by the wave as shown by Gutenberg (1936) but in the case of a wave transformation, the expression is not so simple.

For the PS wave and adapting Gutenberg's procedure for PP, it may be shown that the energy per unit area arriving at the surface of the ground is

$$D_{PS} = \frac{C}{\Delta} \frac{\sin\theta}{\cos\phi} \frac{d\theta}{d\Delta}, \qquad (4)$$

where

C = energy per unit area at a very small distance from the source,

Δ = spread or total horizontal distance travelled

θ = angle of incidence of the P wave

and

ϕ = angle of reflection of the S wave.

Now

$$\Delta = h(\tan\theta + \tan\phi),$$

where

h = depth of the reflecting surface,

so that

$$\frac{d\Delta}{d\theta} = h\left(\sec^2\theta + \sec^2\phi k\frac{\cos\theta}{\cos\phi}\right),$$

where

$k = \dfrac{\sin\phi}{\sin\theta}$ is the ratio of the velocities of the S and P waves.

Substituting in (4), we obtain after some manipulation

$$D_{PS} = \frac{C\sin^2\theta}{h^2\sin(\theta+\phi)(\sin\theta\sec^3\theta+\sin\phi\sec^3\phi)}. \quad (5)$$

Now the displacement in the wave relative to the initial displacement is given by $\sqrt{D_{PS}/C}$. Figure 6 shows Δ/h as the abscissa and $h\sqrt{D_{PS}/C}$ as the ordinate, so that the displacement factor for any values of Δ and h may be quickly determined. In computing, we note that $k=0.5$.

The corresponding energy spread factor for PP is

$$\frac{D_{PP}}{C} = \frac{\cos^2\theta}{4h^2}$$

so that

$$h\sqrt{\frac{D_{PP}}{C}} = \frac{\cos\theta}{2}. \quad (6)$$

Figure 6 also shows the variation of this expression against $\Delta/h = 2\tan\theta$ as abscissa, and it is to be noted that at the shorter distances the attenuation due to the spread of PS is less than that of PP while, at the greater distances, the converse is true. At a distance corresponding to $\Delta/h=2$, the displacements are approximately equal.

It is of some interest here to consider the spread factor for an SP reflection. A priori, it would seem to be identical with (5) but such is not the case. Interchanging θ and ϕ in (4), we have

$$D_{SP} = \frac{C}{\Delta}\frac{\sin\phi}{\cos\theta}\frac{d\phi}{d\Delta} \quad (7)$$

and

$$\frac{d\Delta}{d\phi} = h\left(\sec^2\phi + \frac{\sec^2\theta\cos\phi}{k\cos\theta}\right).$$

Hence

$$D_{SP} = \frac{C\sin^2\phi}{h^2\sin(\theta+\phi)(\sin\theta\sec^3\theta+\sin\phi\sec^3\phi)}. \quad (8)$$

Comparing (5) with (8) we find that

$$\frac{D_{PS}}{D_{PS}} = \frac{\sin^2\theta}{\sin^2\phi} = \frac{1}{k^2} \quad (9)$$

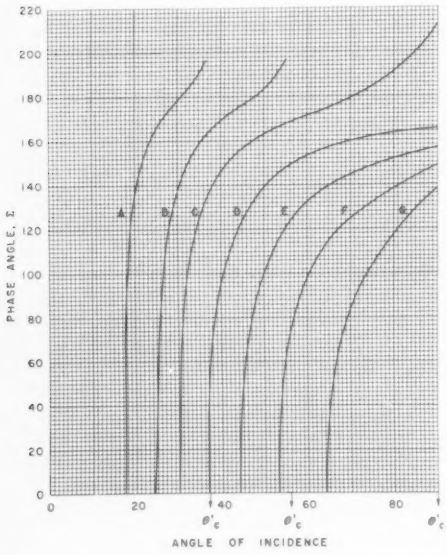

FIG. 5. Phase angles, Σ, of PS wave for varying angles of incidence and impedance ratios.

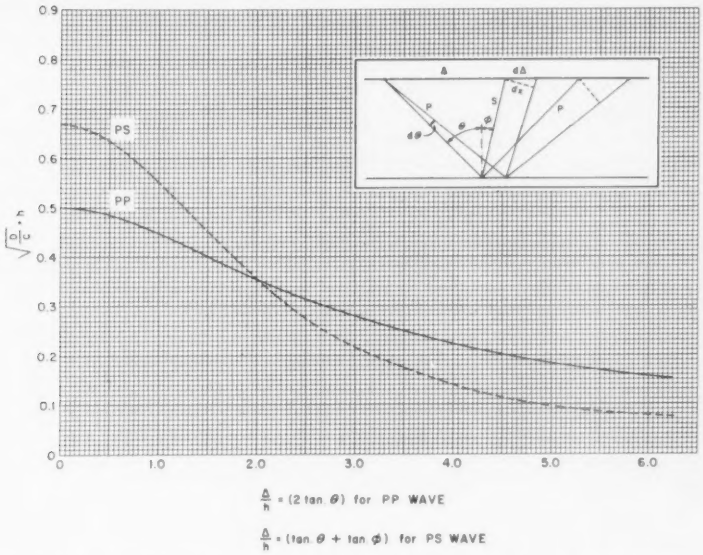

FIG. 6. Spread factor $\sqrt{D/C}$ for varying distances, Δ, and depths, h; PP and PS waves.

so that the displacement in PS is twice that in SP, when $k=0.5$.

GROUND DISPLACEMENT ON ARRIVAL PLANE WAVES

Expressions for the horizontal and vertical components of ground displacement when incident P or SV waves arrive, have been given by Jeffreys (1926) and are also discussed in Ewing, Jardetzky and Press (1957). Following Jeffreys, the expressions for the P wave are:

$$(10)\qquad \frac{u}{U} = \frac{8\alpha\beta(\beta^2+1)^{1/2}}{(\beta^2-1)^2+4\alpha\beta} = B_{Pu}$$

and

$$\frac{w}{U} = \frac{4\alpha(\beta^4-1)}{(\beta^2+1)^{1/2}\left[(\beta^2-1)^2+4\alpha\beta\right]}$$

$$(11)\qquad = B_{Pw}.$$

For the SV wave we have

$$(12)\qquad \frac{u}{U} = \frac{-2\beta(1+\alpha^2)^{1/2}(1+2\alpha^2)}{(1+2\alpha^2)^2+\alpha\beta} = B_{Su}$$

and

$$(13)\qquad \frac{w}{U} = \frac{2\alpha\beta(1+\alpha^2)^{1/2}}{(1+2\alpha^2)^2+\alpha\beta} = B_{Sw}$$

where

U = displacement amplitude in incident wave,
u, w = horizontal and vertical displacement components, respectively, of the ground,

and

α, β = cotangents of angles of reflection of the P and S waves respectively.

These expressions differ from Jeffreys' since he had assumed that $V_P/V_S=\sqrt{3}$ or $\beta^2=2+3\alpha^2$, whereas in our case with $V_P/V_S=2$ we have

$$\beta^2 = 3 + 4\alpha^2. \qquad (14)$$

By using (14) the above displacement ratios may easily be calculated for angles corresponding to varying values of α and β. They are shown in Figures 7 and 8.

It is clear from (12) and (13) that for an SV wave approaching the surface, the horizontal displacement of the ground is 180 degrees out of phase with respect to the vertical displacement. This provides a useful means of discriminating between the arrival of P and SV waves on seismograms where both displacement components are being recorded. However, we see from (14) that if $\beta<\sqrt{3}$, α is imaginary and both the

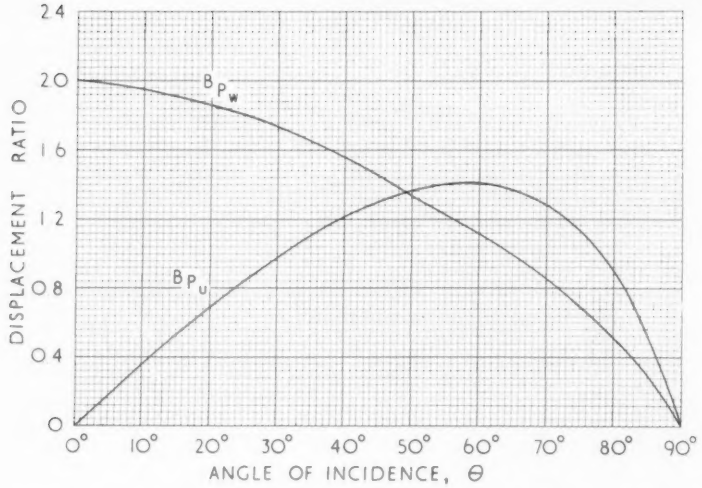

FIG. 7. Ratio of horizontal displacement of ground, B_{Pu}, and vertical displacement of ground, B_{Pw}, to displacement of incident plane P wave, for varying angles of incidence, θ.

vertical and horizontal displacement of SV will then involve phase differences. This will not affect us since in our PS reflection, $\beta > \sqrt{3}$.

It will be noted that B_{Pw} and B_{Su} are both equal to 2, apart from the change in sign, when θ and ϕ are zero; but the relatively large negative value of 3.45 for B_{Su} when $\phi = 30$ degrees is peculiar; Jeffreys, using $V_P/V_S = \sqrt{3}$, finds a corresponding value of $+4.91$, the positive sign apparently being in error.

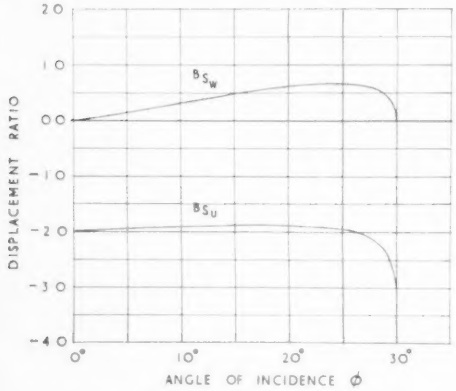

FIG. 8. Ratio of horizontal displacement of ground, B_{Su}, and vertical displacement of ground, B_{Sw}, to displacement of incident plane S wave, for varying angles of incidence, ϕ.

VARIATION OF GROUND DISPLACEMENT DUE TO REFLECTED WAVES WITH DISTANCE

We may now combine the three steps in our analysis to yield the final relative component displacements due to the PP and PS waves reaching the surface of the ground, under the assumption that the overburden is uniform in velocity which implies that the c and γ in (1) are equal to α and β, respectively.

For PP we have

$$(A_w)_{PP} = B_{Pw}\sqrt{\frac{E_1}{E}\frac{D_{PP}}{C}} \tag{15}$$

and

$$(A_u)_{PP} = B_{Pu}\sqrt{\frac{E_1}{E}\frac{D_{PP}}{C}}. \tag{16}$$

For PS we have

$$(A_w)_{PS} = B_{Sw}\sqrt{\frac{cF_1}{\gamma E}\frac{D_{PS}}{C}} \tag{17}$$

and

$$(A_u)_{PS} = B_{Su}\sqrt{\frac{cF_1}{\gamma E}\frac{D_{PS}}{C}}. \tag{18}$$

It will, of course, be appreciated that these final displacements are all relative to the initial displacement in the *P* wave which we assume to be unity. The term c/γ in (17) and (18) enters by virtue of the form of the energy equation (1).

As in the case of Figure 6, it is desirable to express graphically the above displacement variations in a form whereby values can be easily determined for any depth and any observation distance, and Figures 9 to 13 are so constructed for the five impedance ratios, *C* to *G*.

It is seen that there are interesting variations of peak displacements through the various curves. Figure 14 shows a plot of these peak values for Ah against impedance ratio, r. Peak values in Cases A and B, at the lower values of r, have been added, except for those corresponding to *PS* in Case A; peak values here are not available as the energy curve in Figure 2 was not sufficiently investigated.

It is to be noted, firstly, that whereas the peak values of $(A_w)_P$ and $(A_w)_S$ and, to a less extent

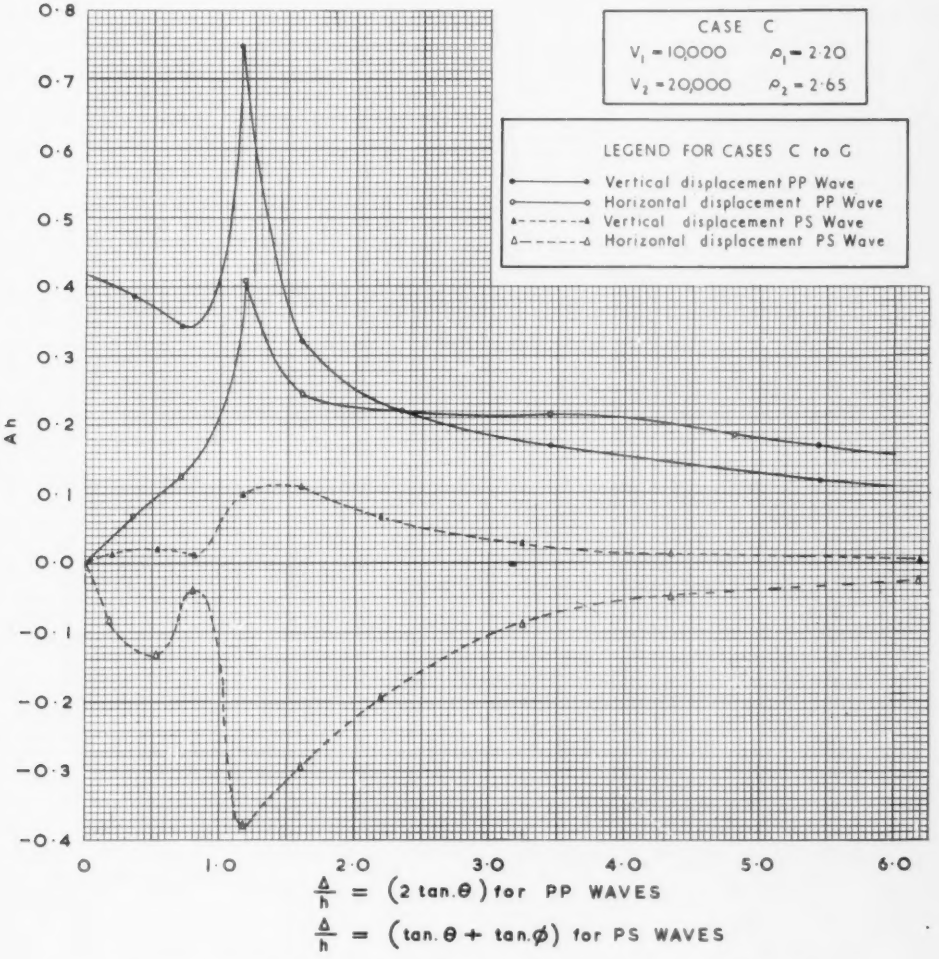

FIG. 9. Resultant horizontal and vertical displacement ratios, A, of ground for *PP* and *PS* waves for varying distances, Δ, and depths, h. Case C ($r=0.42$).

the peak value of $(A_u)_S$, are practically inversely proportional to r, the peak value of $(A_u)_P$ has a maximum at $r=0.58$. Secondly, $(A_w)_P=(A_u)_P$ at $r=0.70$ and thirdly $(A_u)_P=(A_u)_S$, without regard to sign, at $r=0.36$.

The second observation means that with an overburden velocity greater than about 15,000 ft/sec, a horizontal geophone would be more effective than a vertical geophone in registering *PP* at its peak value. This is also true, of course, for distances greater than the peak distance. For overburden velocities less than 15,000 ft/sec, the greater effectiveness of the horizontal geophone occurs at certain distances beyond the peak distances as Figures 9 to 11 indicate. Strangely enough, the observational distance at which this change takes place is given when Δ/h is about 2.4 in each of the three figures.

THE *SP* REFLECTION

Although we are not primarily concerned in this paper with reflections from incident shear waves, we shall here investigate the vertical and horizontal ground displacements of an *SP* reflection in Case C.

In comparison with a *PS* reflection not only is the spread factor different as expressed by (5) and (8) but there is a difference in the ratio of the reflected and incident displacements at the interface. Whereas the ratios of the energies reflected

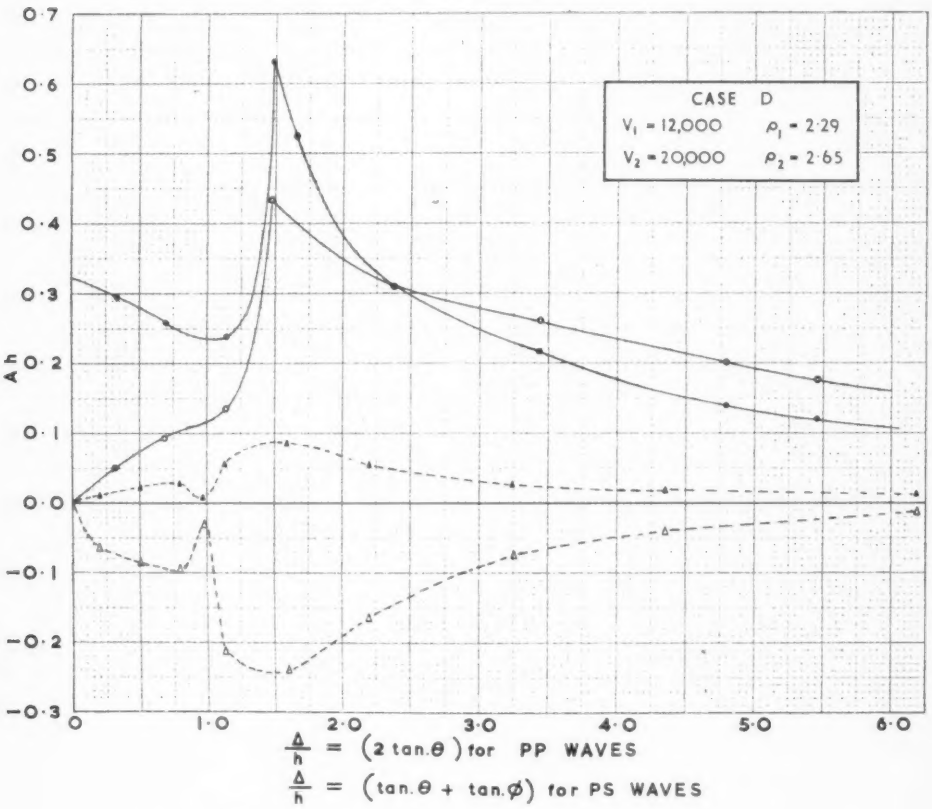

FIG. 10. Resultant horizontal and vertical displacement ratios, A, of ground for *PP* and *PS* waves for varying distances, Δ, and depths, h; Case D ($r=0.52$).

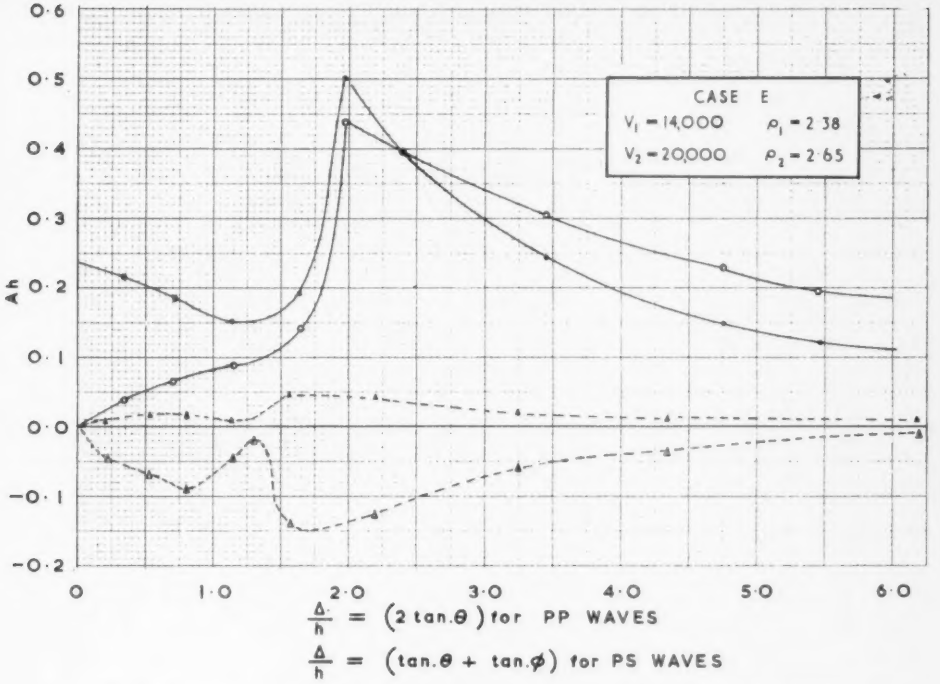

FIG. 11. Resultant horizontal and vertical displacement ratios, A, of ground for PP and PS waves for varying distances, Δ, and depths, h; Case E ($r=0.63$).

are the same in both systems, the displacement ratios are given by

$$\frac{B_1}{A} = \sqrt{\frac{c}{\gamma}\frac{F_1}{E}} \quad \text{for } PS \tag{19}$$

and

$$\frac{A_1}{B} = \sqrt{\frac{\gamma}{c}\frac{E_1}{F}} \quad \text{for } SP. \tag{20}$$

The first expression is evident from (1) while the second follows by analogy for an incident S wave.

At the surface of the ground we then have

$$(A_w)_{SP} = B_{Pw}\sqrt{\frac{\gamma}{c}\frac{E_1}{F}\,D_{SP}} \tag{21}$$

and

$$(A_u)_{SP} = B_{Pu}\sqrt{\frac{\gamma}{c}\frac{E_1}{F}\,D_{SP}}. \tag{22}$$

Comparing (21) and (22) with (17) and (18) we obtain

$$\frac{(A_w)_{SP}}{(A_w)_{PS}} = \frac{0.5\gamma\ B_{Pw}}{cB_{Sw}} \tag{23}$$

and

$$\frac{(A_u)_{SP}}{(A_u)_{PS}} = \frac{0.5\gamma\ B_{Pu}}{cB_{Su}} \tag{24}$$

if $\sqrt{D_{SP}/D_{PS}}$ is our assumed value of 0.5 from (9).

Figure 15 shows the variation of the ground displacements of (21) and (22) with distance and also those of (17) and (18) for comparison, in Case C. We see that the vertical movement for

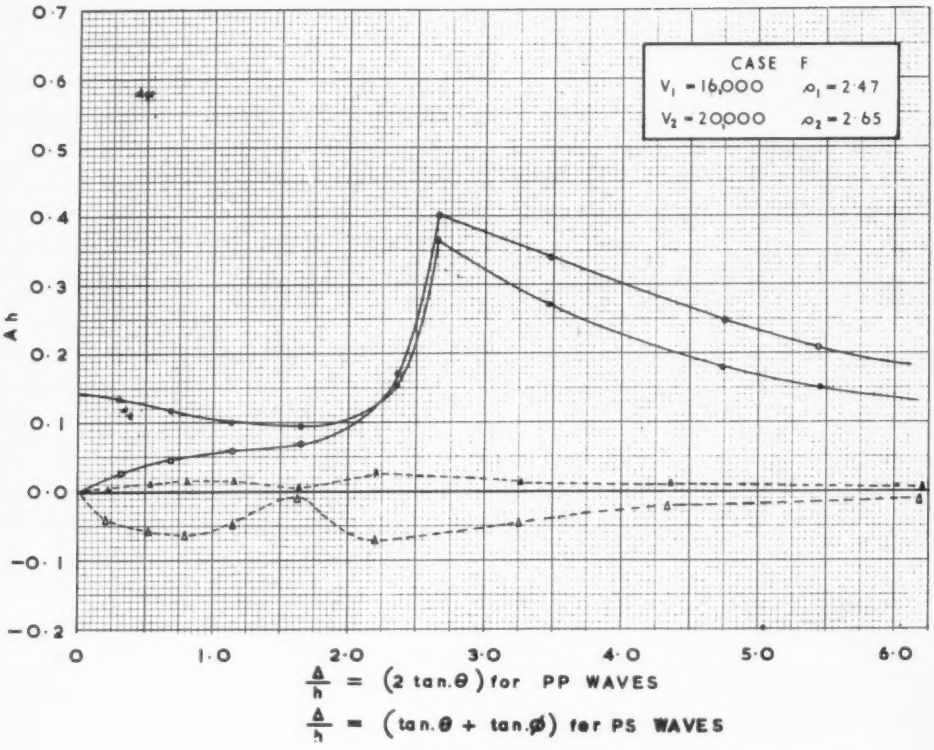

FIG. 12. Resultant horizontal and vertical displacement ratios, A, of ground for PP and PS waves for varying distances, Δ, and depths h; Case F ($r=0.75$).

all distances greater than zero is much greater for SP than for PS, especially at small and large values of Δ/h. In the case of horizontal movement SP is greater than PS, without regard to sign, when $\Delta/h>1.6$; when $\Delta/h<1.6$, the converse is true.

REFLECTIONS FROM THE BASE OF A HIGH VELOCITY LAYER OVERLAIN AND UNDERLAIN BY LOW VELOCITY MATERIAL

A problem in wide-angle reflection measurements concerns the displacement amplitudes of reflected P and S waves from the base of a high velocity layer. In faulted foothill country, for example, this layer could be an overthrust limestone sheet, the underlying beds being a repetition of the low velocity sandstones and shales above.

Figures 16 and 17 portray the energy partitions in this condition and corresponding to our Cases C to G. At normal incidence we have, of course, the same energy return as in the case of the low-high impedance ratio but nowhere does the reflected energy in the S wave become appreciable. The displacements of all components at all angles of incidence suffer a phase change of 180 degrees but there are no other phase changes. Once again, it is worth noting that the reflected or refracted energy in the S wave at its peak value varies approximately as the square of the impedance difference.

In order to determine the horizontal and vertical displacement components of the reflected P wave at the surface of the ground, we proceed as before, making allowance for the division of energy at the upper surface of the high velocity bed; but it is necessary to specify the depth and thickness of this bed. The final component displacement curves for a specific case are shown in Figure 18, in which the vertical components fall

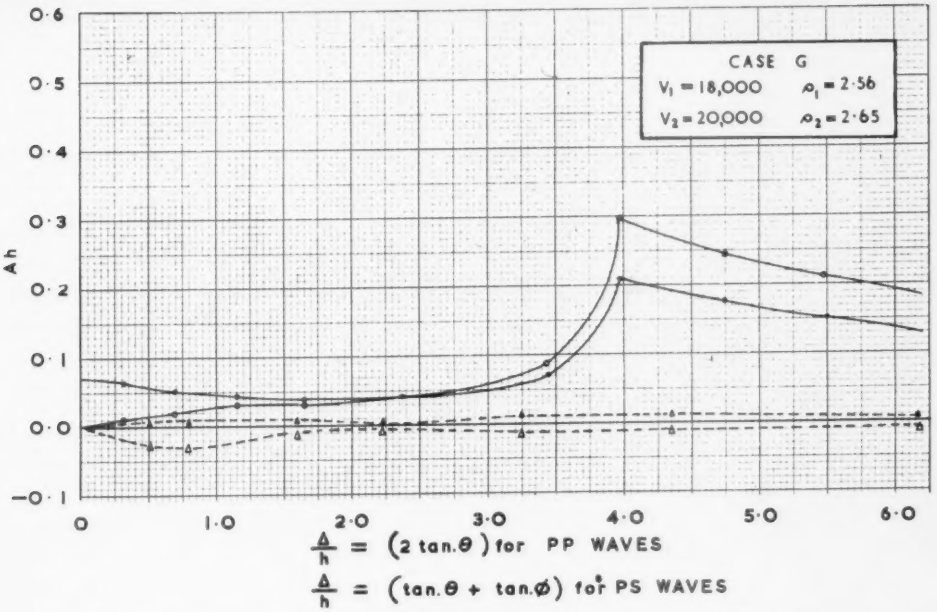

FIG. 13. Resultant horizontal and vertical displacement ratios, A, of ground for PP and PS waves for varying distances, Δ, and depths, h; Case G ($r=0.87$).

appreciably from normal incidence and rise to only small peak values with increasing distance. These displacements are, however, very small compared with the peak displacements to be expected from the upper surface of the high velocity bed.

Thus, in Figure 18, the vertical displacement for Case C at normal incidence is 0.286×10^{-4} unit and at its peak value 0.126×10^{-4} unit. For reflections from the upper interface, Figure 9 with $h=10{,}000$ ft shows that the corresponding values are 0.416×10^{-4} and 0.746×10^{-4} unit, respectively. At normal incidence, both systems yield good measures of displacement, but there would be relatively small peak values for reflections from the base of the high velocity layer. For the highest impedance ratio, Case G, the corresponding displacement values are 0.052×10^{-4} and 0.053×10^{-4} unit for reflection from the lower interface and 0.070×10^{-4} and 0.210 unit from the upper interface.

The horizontal displacements of Figure 18 show that there is an optimum value of the impedance ratio for maximum ground movement at

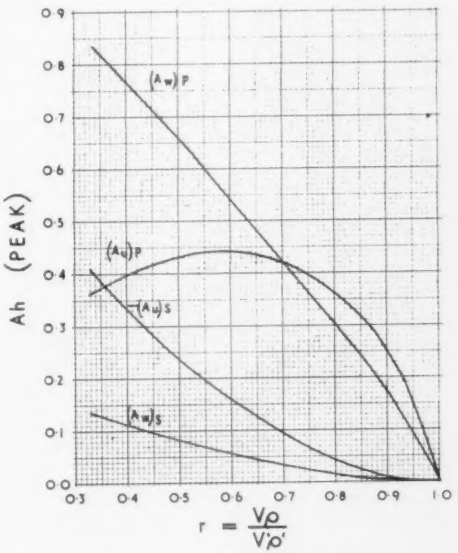

FIG. 14. Resultant peak displacement ratios, A, of PP and PS for varying impedance ratios, r and depth h; u and w refer to horizontal and vertical motion, respectively.

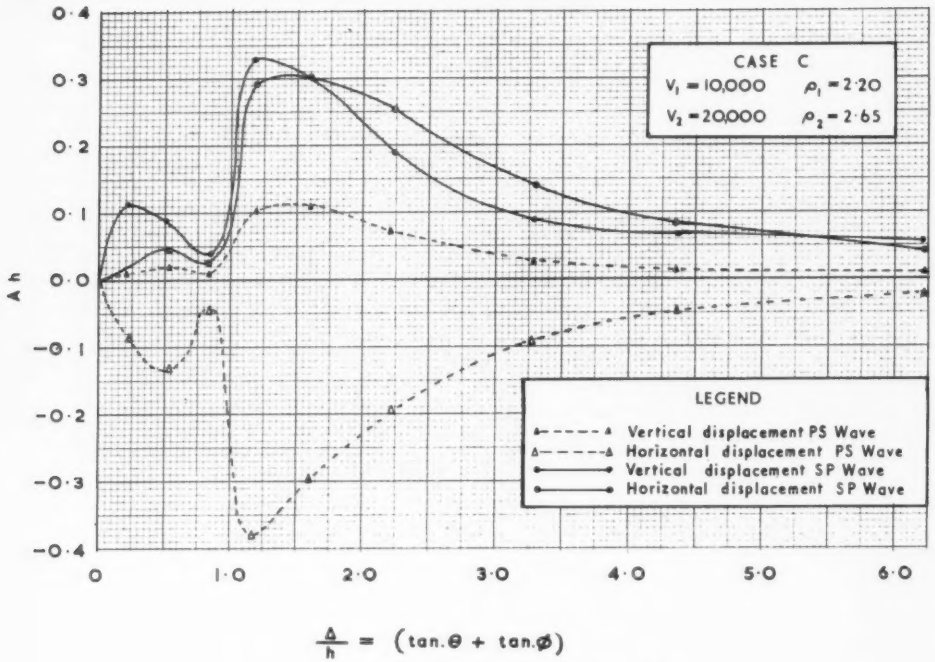

FIG. 15. Comparison of ground displacements of *PS* and *SP* waves.

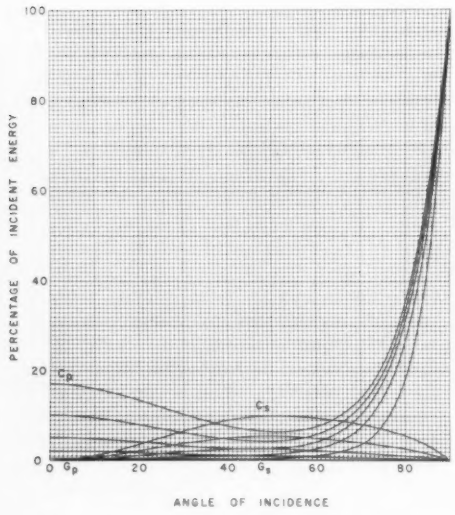

FIG. 16. Percentage of incident energy of *P* wave reflected as *P* and *S* waves from the base of a high velocity layer underlain by low velocity material.

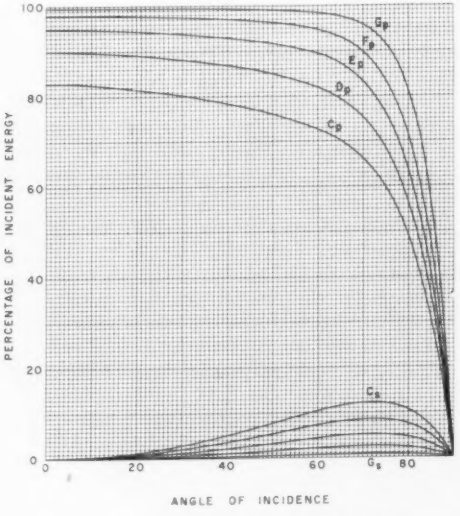

FIG. 17. Percentage of incident energy of *P* wave refracted as *P* and *S* waves from the base of a high velocity layer underlain by low velocity material.

the peak value. This ratio corresponds to Case E, or an r of about 0.6 and a similar relationship was seen to hold for the case of reflections from the upper interface (see Figure 14).

Nevertheless, as in the case of the vertical displacements, these horizontal displacements at wide-angle reflection distances are very small compared with those from the upper interface. At normal incidence where the vertical displacement of the *PP* wave from the lower interface is not small, an interference effect (in which the thickness is also a factor) on the reflected wave form from the upper interface may assume some importance and this is, of course, recognized in the construction of synthetic seismograms from velocity logs.

With regard to an *S* wave arriving at the ground surface whether it is generated at the lower or upper interface, it is clear from the energy curves that its component displacements would be smaller still than those for the *P* wave.

PRACTICAL APPLICATIONS

In the West Canadian foothills, well velocity surveys reveal a number of discrete velocity units within the Mississippian limestone overburden. Departures from our simple theoretical treatment will result from (a) the loss of energy of a *P* wave

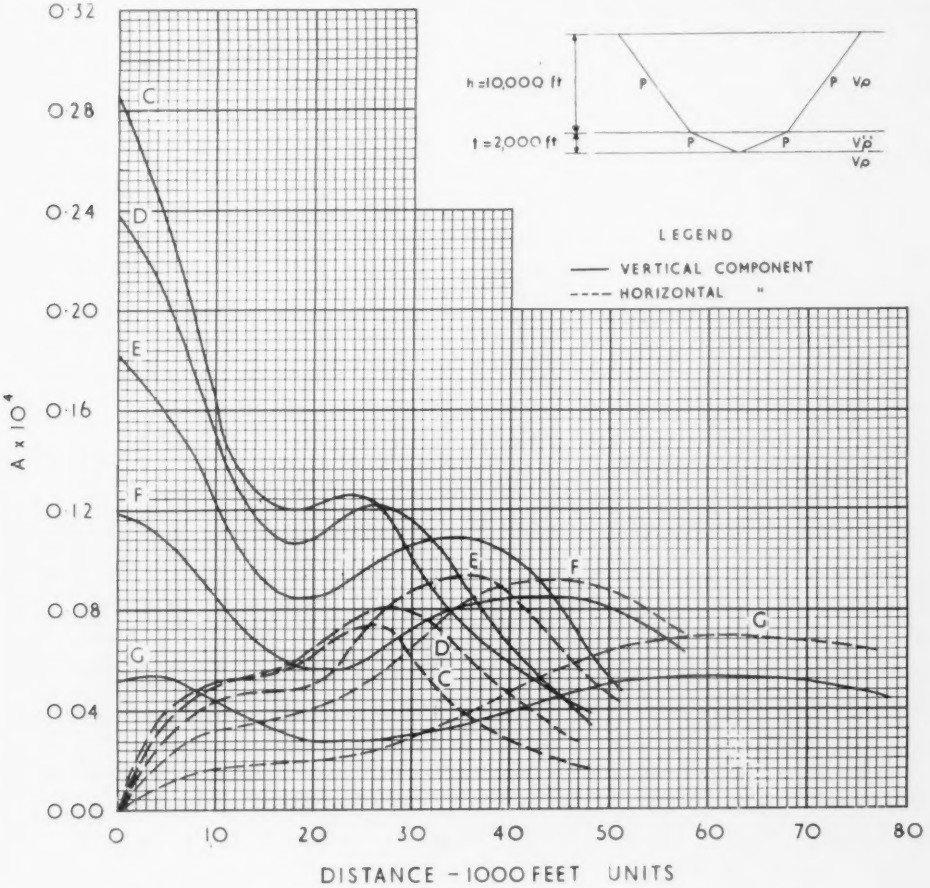

FIG. 18. Resultant horizontal and vertical displacement ratios, A, of ground for *PPPP* wave for varying distances and impedance ratios.

in the overburden due to wave transformations at contrasting interfaces, (b) an increase in the path length of the reflected wave and therefore in the spread factor, and (c) the fact that the angle of incidence at the limestone is not necessarily the same as that at the surface of the ground. We shall now consider these factors, in turn, confining our attention to a *PP* wave.

Energy Loss

If there are n discrete velocity units resting on the limestone, the fraction of the original energy arriving at the ground surface may be shown to be $E_r(P_{t=n-1}^{t=1} e_t^2)$ where E_r is the fraction of the incident energy reflected at the limestone, e_t is the fraction of the incident energy transmitted at each interface in one direction and the term in brackets is the product of all such fractions along *PP*.

Table I gives the velocity distributions above the Mississippian limestone in four widely spaced central foothills wells. Low velocity weathering is virtually absent (although this assumes some importance in river valleys) but there appears to be a distinctive uppermost formation, the presence of which is always detected in first event refraction surveys. The thickness of the remaining overburden and its average velocity are also shown in these columns while the range of the variation of velocity in each successive 1,000 ft unit is given in the fourth column. There is no systematic increase of velocity with depth although the high velocity occurs in the lowest unit.

Now when the impedance changes from unit to unit in the overburden are relatively small, then, in considering energy transmission, we may neglect the derived S waves at any interface. This follows from an inspection of the energy curves in Figures 2 and 3. Such being the case, we have the well-known expression

$$\frac{a_r}{a} = \frac{V_2\rho_2 \cos\theta_1 - V_1\rho_1 \cos\theta_2}{V_2\rho_2 \cos\theta_1 + V_1\rho_1 \cos\theta_2} \qquad (25)$$

where θ_1 and θ_2 are the angles of incidence and refraction at the interface, and a_r/a is the ratio of the amplitudes of displacement in the reflected and incident waves.

Since the impedance differences are small, it follows that the difference between θ_1 and θ_2 is also small so that we may write

$$\frac{a_r}{a} \cong \frac{\Delta V\rho \cos\theta}{2V\rho \cos\theta}$$

$$\cong \Delta/2 \log (\rho V \cos\theta) \qquad (26)$$

which, apart from the cosine term, is the same as that used in computing synthetic seismograms from continuous velocity logs.

We now apply (26) to the individual velocity units in the case of Well No. 2, using the velocity-density assumption we made at the beginning of this paper and considering a *PP* wave incident on the limestone at the critical angle. This angle is given by $\theta_c = \sin^{-1} 14{,}300/20{,}000$ or 45.6 degrees, while $\sin\theta = V/20{,}000$. Table II gives the results.

Now

$$e_t = 1 - (a_r/a)^2,$$

and since a_r/a is very small, we may write

$$P_{t=10}^{t=1} e_t^{\ 2} = 1 - \left[\sum_{t=10}^{t=1} (a_r/a)_t^{\ 2}\right]^2. \qquad (27)$$

Evaluating (27) we find that the amount by which E_r is reduced due to the loss of energy by reflections at the ten interfaces is 0.992, or the displacement, A_r, is reduced by 0.996.

A similar calculation when the angle of incidence at the limestone is 70 degrees and $\sin\theta = \sin 70 \text{ degrees} \cdot V/14{,}300$, yields an energy reduction factor of 0.881 or a displacement reduction factor of 0.939. At the greater wide-angle reflection distances, therefore, the displacement in *PP* is only slightly impaired and this will be clearly applicable to the other wells in Table 1.

Now the average overburden velocity, as computed from Table 2, is 13,200 ft/sec and the ap-

Table I

Well	Thickness (ft)	Velocity (ft/sec)	Velocity Range (ft/sec)
1	700	11,600	
	11,000	13,300	12,500–14,700
2	1,000	11,400	
	10,000	13,400	12,500–14,300
3	1,300	11,100	
	9,200	13,300	12,500–14,300
4	1,200	10,800	
	8,400	13,700	11,600–15,100

Table II

Unit	$V\times10^{-2}$ (ft/sec)	$V\rho\cos\theta\times10^{-2}$	$a_r/a\times10^4$
1	114	210	
			476
2	131	231	
			86
3	135	235	
			42
4	139	237	
			−259
5	125	225	
			175
6	133	233	
			106
7	141	238	
			−9
8	133	233	
			−87
9	128	229	
			108
10	135	234	
			106
11	143	239	

parent critical angle of reflection therefore becomes $\bar{\theta}_c=\sin^{-1}0.66$ or 41.3 degrees, as against $\theta_c=45.6$ degrees. In the former case, we should expect peak displacements in PP at a distance of 19,300 ft while, allowing for the presence of the individual units, this distance is only slightly more at 19,600 ft.

We next consider the reflected energy at a very large wide-angle reflection distance, in the case when the overburden velocity is averaged. Now, when the true angle of incidence at the limestone is 70 degrees, the horizontal distance travelled by PP is computed from the velocity in Table 2 to be 41,500 ft. At this distance, with the average velocity of 13,200 ft/sec, the angle of reflection would be 62.1 degrees and, by interpolation of the curves in Figure 1, E_1 would be about 67 percent. In the exact case, with the appropriate velocity of 14,300 ft/sec, E_r is 82 percent. Consequently, there is more energy than might be anticipated from the use of an averaged overburden velocity; in terms of displacement, the increase would be 11 percent.

The Spread Factor

Again referring to Table 2, the total oblique distance travelled by PP, at the large angle of reflection of 70 degrees is 47,200 ft, while in the case of the uniform overburden and adhering to the same horizontal distance, the oblique distance is 47,000 ft. The difference is negligible.

Angle of Incidence at the Ground Surface

At the distance of 19,600 ft, when the angle of reflection at the limestone, θ_1, is 45.6 degrees, the angle of incidence of PP at the surface of the ground, θ_g, may be computed to be 34.7 degrees. From Figure 7 we then find that the true values of B_{Pw} and B_{Pu} are 1.66 and 1.08 respectively. In the case of the uniform overburden we have $\theta_1=\theta_g=41.3$ degrees and $B_{Pw}=1.52$ and $B_{Pu}=1.23$. The adoption of the latter assumption, therefore, results in a too small value by 8 percent for the vertical displacement and a too large value by 14 percent for the horizontal displacement.

At the larger distance of 41,500 ft, $\theta_1=70$ degrees, $\theta_g=48.5$ degrees, $B_{Pw}=1.36$ and $B_{Pu}=1.35$. In the condition of $\theta_1=\theta_g=62.1$ degrees we have $B_{Pw}=1.06$ and $B_{Pu}=1.40$, showing that the former is too small by 22 percent and the latter too large by 4 percent.

Let us now examine the effect such discrepancies have on the final displacement curves. With an average overburden velocity of 13,200 ft/sec, we are dealing with a case a little more than midway between Cases D and E. By interpolation between the curves in Figures 10 and 11 we find that at the smaller distance when $\Delta/h=1.78$, the vertical and horizontal displacements are given by $Ah=0.52$ and $Ah=0.44$, respectively; applying the corrections Ah (vertical) would be 0.57 and Ah (horizontal) 0.39. At the larger distance when $\Delta/h=3.77$, the interpolated curves give Ah (vertical) $=0.21$ and Ah (horizontal) $=0.26$; applying the corrections Ah (vertical) $=0.22$ and Ah (horizontal) $=0.25$.

In practice, however, we may not have well velocity information available so that the interbedding and velocity distribution throughout the overburden are unknown. But in all cases in the central foothills, we can measure the thickness and velocity of the uppermost formation by first event refraction work while the average velocity throughout the overburden may be determined by means of a T^2-X^2 plot of the wide-angle reflections. Subsequently, we can assign a thickness and average velocity to that part of the overburden underlying the uppermost formation.

Let us suppose that we have obtained the thicknesses and velocities for Well No. 2 in Table

1. Then at the distance of 19,600 ft, it may be shown that $\theta_1 = 41.9$ degrees and $\theta_0 = 34.6$ degrees; the latter is almost identical with the multilayer value of 34.7 degrees. At the distance of 41,500 ft, $\theta_1 = 63$ degrees and $\theta_0 = 49.2$ degrees; the latter is comparable with the multilayer value of 48.5 degrees.

The above discussion for the *PP* wave will also be applicable to limestone overburdens such as those specified in the other wells of Table 1 and in other areas with similar velocity conditions. It is only at the larger wide-angle reflection distances, however, that the vertical displacement appears to be significantly greater than our curves suggest, but the horizontal displacement at such distances is hardly affected.

GENERAL DISCUSSION

In identifying a *PP* or *PS* event on a seismic record, not only is a good signal/noise ratio necessary, but good correlation over as great a distance range as possible. In the central foothills of Western Canada, where the depth of the limestone reflector is of the order of 10,000 ft, and the geology not too complicated, the travel time of the vertical component of *PP* has been measured in the range of 10,000 ft to 60,000 ft, the critical angle of reflection being about 45 degrees. Here, the event is well clear of earlier motion and later motion due to the direct *S* and Rayleigh waves.

For shallow reflectors, *PP* may not be identified and the horizontal geophone measurements of Ricker and Lynn (1950), referred to in the introduction, provides an example. In their case, the parameters involved were: $V_P = 6{,}500$ ft/sec, $V_S = 2{,}340$ ft/sec, $V'_P = 10{,}300$ ft/sec, and $h = 2{,}000$ ft. The strong *PP* motion expected at and beyond the critical distance would occur only about 0.1 sec later than the first event and here the records show considerable background. However, *PS* in one case is shown to be well marked in the range of 5,000 to 6,000 ft, and this conforms to the authors statement that the event enters rather suddenly when the distance is two to three times the depth.

As in their case V_P/V_S is significantly larger than 2.0, the value assumed in our theoretical investigations, we cannot, unfortunately, use our displacement curves to check whether the experimental distance conforms to theoretical expectation.

Both *PP* and *PS* events have been recognized in the model experiments of Press, Oliver and Ewing (1954). Here, the vertical motion was being measured but whereas *PP* was identifiable with difficulty over a very restricted range, *PS* was strong and correlatable over a much greater range only limited by the entry of the direct *S* event. Levin and Hibbard (1955) have demonstrated the existence of a strong and persistent *PP* event while *PS* is subjected to much interference. It is because of interference effects that it has not been possible to measure the variations of displacement with distance of specific reflected events, in any of the published work.

For direct refracted events such as *PP'* and *PS'*, however, interference is not so marked and Clay and McNeil (1955) have been able to make the desired measurements of the vertical displacement. They show that the observed values will satisfy the theoretical values based on plane wave theory (employing steps one and three in our analysis), provided the spread factor is more nearly proportional to the inverse square of the distance travelled, rather than to the inverse of distance for a *PP* wave. The authors point out that this large displacement spread factor is to be expected in the proximity of a displacement source, a condition satisfied in their experiment.

In the same paper, Clay and McNeil have investigated, theoretically, the variation of vertical displacement of *PP* and *PS* at the free surface of their model before and after correcting for the experimentally derived spread factor; the appropriate curves are shown in their Figure 3. The model, with impedance ratio of $(7{,}300 \times 2.0)/(18{,}400 \times 2.7)$, is equivalent to our anomalous Case B, which we have only considered in energy distribution and phase changes at the reflector. In regard to the small negative displacement shown at a distance of 2 inches for *PS*, in their Figure 3, this would imply the existence of a small maximum in the energy curve for *PS* at the interface and this is not disclosed in our Figure 2. Furthermore, the existence of a negative phase angle between distances of 2 and 4 inches implies a time gain in the arrival of the *PS* event which would seem to have no physical meaning.

Gutenberg (1912) has determined the energy distribution curves for a variety of solid-solid contrasts to be expected in seismological studies and it is to be noted that the results for his Case 4 are about the same as for our Case F, the two

cases having comparable parameters.

The extension of energy curves beyond the second critical angle has been evaluated by Nafe (1957) in which paper his Case 1 is similar to our Case B, with an impedance ratio of 0.33.

Of particular interest in regard to phase changes is the work by Malinovskaya (1957). He confines his attention to *PP* waves in four cases defined by velocity ratios of 4.8, 2.5, 1.8 and 1.3; and density ratios of 1.3, 1.24, 1.13 and 1.0, respectively. In our system these give impedance ratios of 0.16, 0.32, 0.49 and 0.77, so that the second is equivalent to our Case B, the third approximates Case D and the fourth, Case F. His derivation of the vertical ground displacement for *PP* is identical with ours and the change of phase with distance beyond the first critical angle is illustrated by a series of theoretical seismograms.

Malinovskaya agrees that the phase angle in all cases reaches 180 degrees at grazing incidence (see our Figure 4) but finds that for an angle of incidence of 60 degrees ($r=0.32$ or Case B), the maximum phase shift is 250 degrees; this is doubtless an effect associated with the second critical angle. His maximum phase for $r=0.49$ is 184 degrees but we find the phase cannot exceed 180 degrees for $r \gtrsim 0.42$.

The phase changes that occur in wide-angle reflections beyond the critical distance have, of course, a bearing on depth determinations, and it is interesting to see how the foothills studies described by Richards (1960) will be affected. Referring to Figure 4 in his paper, we find that at a distance of 60,000 ft, where the angle of reflection is about 67 degrees and the appropriate velocity 13,000 ft/sec, the phase lag obtained from Figure 4 of the present paper is 160 degrees. With a wave period of about 0.08 sec, this phase lag is equivalent to 0.035 sec, and the theoretical reflection time plotted at this distance should therefore be increased by this amount. The discrepancy between the observed time and the theoretical time is increased from 0.12 to only about 0.16 sec which, as before, could also be attributed to the assumption that the overburden was uniform whereas it is known to consist of more than one discrete layer.

We now consider the effect of the phase lag in Table 1 and Figure 11, of this earlier paper by Richards. We first of all accept the computed depths and velocities given in Table 1 so as to determine to a first approximation the angles of reflection and the slant velocities V_θ to which the observed reflection, T_r, refers. From our phase curves, we then note the appropriate time lag involved. In the first row of the table we find that for depth calculation purposes, T_r should be decreased from 2.930 to 2.903 secs. As a result, it is found that k is increased from 1.08 to 1.1, which is now more in keeping with the values determined by controlled experiment, as indicated in Figure 2 or 3 of the earlier paper and also with an unpublished value of $k=1.11$ determined by the well geophone method in a foothills well. On applying the phase correction to other values of T_r, we find normal velocities and depths are changed by only small amounts; for example, at the extreme distance of 12,100 ft from the well, T_r should be 3.035 instead of 3.053 secs and the recomputed normal velocity and depth 13,500 ft/sec and 13,800 ft, as against the uncorrected values of 13,650 ft/sec and 13,950 ft.

The development of a family of ground displacement-distance curves for reflected waves of the *SS* and *SP* types should prove of interest, for even when the source is essentially dilational as it is in seismic exploration, important transverse motion as a secondary effect also occurs. At times a long distance refraction work, the vertical displacement in the *SSS* wave reaching the surface is greater than in the *PPP* wave; such was the case for those time-distance curves given by Richards (1933).

It should be noted, however, that an incident *S* wave, in general, consists of both *SV* and *SH* motion, and the reflection coefficients of either type at an interface differ. Gutenberg (1912) gives curves for the energy distribution of *SH* in special solid-solid cases while Jeffreys (1926), in considering the effects at the surface of the ground, points out that for all angles of incidence there is complete reflection and that the horizontal displacement is twice that in the incident wave. There should, of course, be no *SH* movement on the arrival of a *PS* event and this criterion could be used with advantage in the latter's identification. For this purpose good three-way geophones are now on the market.

The introduction of a separate "spread factor" may be controversial, especially in the case of wave transformation. How nearly plane wave theory, coupled with this factor, satisfies our problem of wide-angle reflections from deep structures can only be determined when the

more difficult expressions for spherical waves have been evaluated. These expressions also take into account the production of the Rayleigh wave when a spherical wave reaches the ground surface. In the experimental work described by Richards (1960) however, his Figure 5 provides no evidence that a derived Rayleigh wave exists while the lower part of his Figure 4 indicates close agreement between experimental and theoretical vertical surface displacements for *PP*, when the theory is that discussed in the present paper. Experimental evidence for the existence of *PS* from deep structures and the variation with distance of the surface displacements it creates is very desirable.

In regard to the practical applications of our idealized final displacement curves, it should be noted that the peak displacement relationships shown graphically in Figure 14 would be modified but the general form of the curves would remain. We should, however, expect $(A_u)_P$ and $(A_w)_P$ to be equal at a somewhat greater value of r than 0.70.

Modifications to the ground motion in the case of *PS* waves may also be found in a similar way to that outlined above for *PP* waves, the energy factor (a) and spread factor (b) remaining, as before, practically unaffected.

CONCLUSIONS

In the case of a uniform overburden, the principal results of our theoretical investigation are:

1. The percentage of the incident energy passing into the critically reflected *PP* wave is more than 95 percent within the range of r considered: namely, 0.23 to 0.87, corresponding to overburden velocities of 6,000 ft/sec to 18,000 ft/sec and a limestone velocity of 20,000 ft/sec.
2. For *PP* at normal incidence, the percentage energy is approximately proportional to the square of the impedance difference, $\Delta(V\rho)$, within the range of r considered. For *PS* and *PS'* at their peak values, this relationship is true provided $r>0.4$.
3. The vertical and horizontal ground displacements of *PS* are opposed in sign whereas those of *PP* have the same sign; this is a useful criterion in distinguishing between the arrival of *PP* and *PS* events on a record.
4. The peak value of the horizontal component of the *PP* event has a maximum at $r=0.6$ or when the overburden velocity is nearly 14,000 ft/sec. The peak values of the vertical component of the *PP* event and of both components of *PS* are approximately inversely proportional to r within the range considered.
5. The horizontal components of the *PP* event at distances beyond the peak distance are greater than the vertical components provided $r>0.7$ ($V>15{,}000$ ft/sec), approximately. For $r<0.7$, the horizontal component is greater only when the distance beyond the peak has reached a certain value.
6. The peak value of the horizontal component of the *PS* event is less than this component of *PP* when $r>0.36$ ($V>9{,}000$ ft/sec), approximately.
7. The horizontal and vertical components of the events that have been reflected at wide angles from the base of a high speed formation lying within low speed formations are very small, compared with those due to reflections from the top of the formation; interference effects derived therefrom may be neglected.
8. For deep structures, it would appear that *PP*, which should arrive in a relatively quiet part of the seismogram, is more readily identifiable; for shallow structures, this event which enters the record soon after the first arrival may suffer interference, in which case *PS* may be better identified.
9. In practice, where the limestone overburden consists of a relatively low velocity upper formation followed by a series of discrete layers with varying velocity, the transmission of energy based on plane wave theory and the spread factor do not sensibly differ from their values determined at an averaged overburden velocity. Modifications to the idealized final displacement curves given in this paper will be necessary, however, on account of the difference between the angles of incidence at the limestone and the ground surface. It is sufficient to determine these modifications by considering the effect the uppermost formation has on the direction of *PP* or *PS*, the remaining overburden having been assigned an average velocity.
10. In computing depths to the limestone, phase time lags which occur at distances beyond

those corresponding to critical angles of reflection should be allowed for, although the corrections involved may be within experimental error. However, in the determination of the anisotropic factor from the results of wide-angle and conventional reflection measurements along profiles suitably disposed about a well, in which the velocity to the limestone is known, the phase correction would appear to be important.

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GEOPHYSICS, VOL. XXVI, NO. 3 (JUNE, 1961), PP. 298–308, 8 FIGS

AN ANALOG SEISMIC CORRELATOR*

F. N. TULLOS† AND L. C. CUMMINGS, JR.†

Abstract: An analog computer has been built to compute the cross-correlation coefficients of multi-trace seismograms. The evaluation program has shown that the computer has greater accuracy than is normally required to compute the cross-correlation functions of short samples of data. Points on the correlation curves are computed and plotted at the rate of approximately 50 points per minute. Scanning is in difference of arrival times (Δt) across the record, with increments of $\frac{1}{2}$ to 16 millisecond. The correlation process is completely automatic with the exception of normalization, which is approximated by holding the total average signal power constant with a ganged attenuator. Analysis of synthetic and actual seismic data indicates that the correlation will be an interpretational aid in areas where the data are poor.

INTRODUCTION

As the known seismic prospects are proved or disproved with the drill, the geophysicist is hard pressed to sharpen his tools and extract more information from his shots, thumps, and vibrations. With the advent of magnetic tape recording and the development of automatic electronic computers, it becomes possible to apply some of the concepts of information theory to the detection and identification of seismic signals.

The Seismic Analog Correlator was developed to evaluate the applicability of the correlation analysis in seismic interpretation. The degree of reliability with which an event may be inferred from seismic data depends upon the number of traces, the length of the sample, the power density spectrum, and the degree of correlation. Correlation techniques may seem inapplicable to seismic data since such data from geologic zones of interest may be short in terms of record time. The potency of correlation techniques depends upon adequately long samples of data. However, this problem can be relieved somewhat by resorting to an ensemble of data traces such as a multitrace seismogram.

The correlator is particularly suited to the detection of coherent signals mixed with random noise and to the detection and separation of signals that might arrive at the same time from separate sources. The desired seismic signals are often obscured by certain types of coherent noise. In some cases, it is possible to separate these undesired noise signals by their arrival angle, or Δt. In these cases, it may be left to the discretion of the interpreter to decide which is the desired and which is the undesired signal. This type of analysis gives the seismic interpreter an objective measure of the quality of a seismic event, based on the degree of similiarity of the individual seismic traces, and a best estimate of the Δt of the events. With these measurements the interpreter can compare the quality of events over different parts of an area.

THEORY

Many criteria have been used to measure the similarity of functions. Probably the most widely used is the least-mean-squared difference criterion. To compare two stationary time functions $f_i(t)$ and $f_j(t)$ by this method, one of the functions is subtracted from the other and the difference is squared and averaged over the time of interest, as shown in Figure 1a. If this average value is recorded and the process is repeated many times, with one of the functions shifted a small time increment for each operation, a new function $D(\tau)$ will be generated where τ is the time shift of $f_i(t)$ with respect to $f_j(t)$. A graphic illustration of

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† Humble Oil & Refining Company, Houston, Texas.

the resulting curve is shown in Figure 1b with $D(\tau)$ plotted versus the independent variable τ. The minimum of the mean-squared difference is the condition for the best fit, and the corresponding value of τ is the amount of time shift necessary to realize this fit.

The above concepts relate to the cross-correlation function as shown below. By definition

$$(1) \qquad D(\tau) = \langle [f_i(t) - f_j(t+\tau)]^2 \rangle_{av}.$$

Expanded this becomes

$$(2) \qquad D(\tau) = \langle [f_i(t)]^2 - 2[f_i(t)][f_j(t+\tau)] + [f_j(t+\tau)]^2 \rangle_{av}.$$

Here $\langle [f_i(t)]^2 \rangle_{av}$ and $\langle [f_j(t+\tau)]^2 \rangle_{av}$ represent the average power of the two functions $f_i(t)$ and $f_j(t+\tau)$. Defining

$$(3) \qquad d(t) = -2\langle [f_i(t)][f_j(t+\tau)] \rangle_{av},$$

the function $d(\tau)$ is a measure of the degree of similarity of $f_i(t)$ and $f_j(t)$ as a function of τ. This function fluctuates about zero in the same way that $D(\tau)$ fluctuates about the line AB, which represents the sum of the average powers of the two original functions. As $f_j(t)$ is shifted with respect to $f_i(t)$, any degree of similarity of $f_i(t)$ and $f_j(t)$ will cause the function $d(\tau)$ to become a minimum for some value of τ; this will be the condition for a least-mean-square fit. If the same $f_i(t)$ and $f_j(t+\tau)$ had been added instead of subtracted for the preceding operation, a new function $F(\tau)$ would have been generated. The function $F(\tau)$ shown in Figure 2b, will fluctuate about the line representing the sum of the average powers of the original functions. Any degree of similarity of the two functions will cause the function $F(\tau)$ to become a maximum at the same value of τ that the function $D(\tau)$ became a minimum. Actually, the function $F(\tau)$ is a mirror image of $D(\tau)$ about the line AB representing the sum of the average pow-

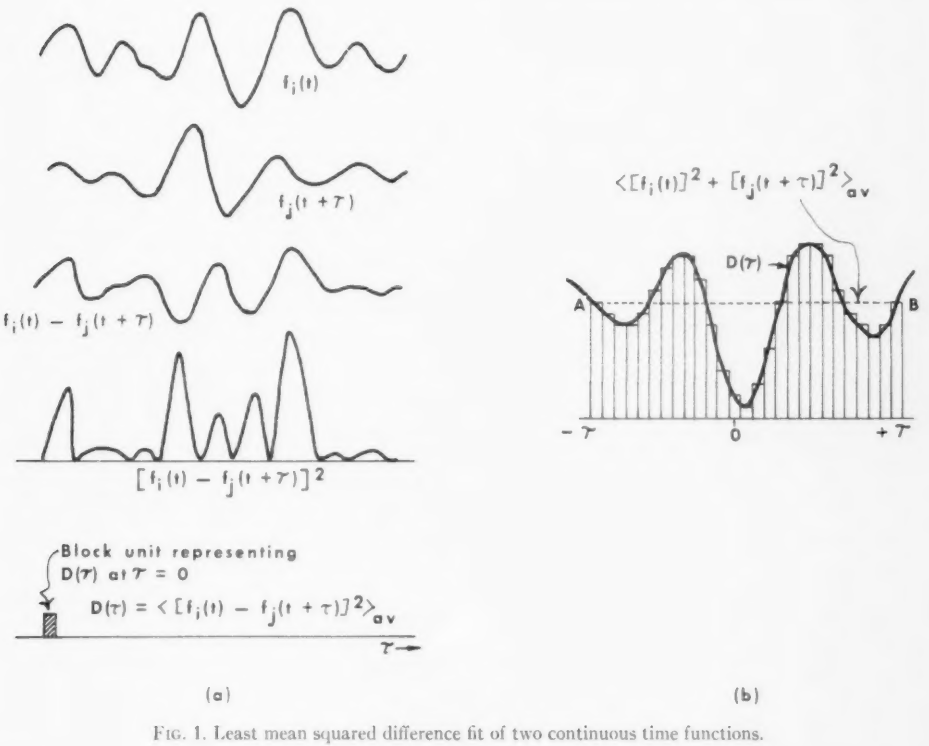

FIG. 1. Least mean squared difference fit of two continuous time functions.

ers of $f_i(t)$ and $f_j(t+\tau)$. Here the variable part

$$f(\tau) = 2\langle [f_i(t)][f_j(t+\tau)]\rangle_{av} \tag{4}$$

may be separated as the significant part; and $f(\tau)$ is closely related to the correlation function.

The normalized finite cross-correlation function $\rho_{ij}(\tau)$ is defined by Goldman (1953, p. 241) by the equation

$$\rho_{ij}(\tau) = \frac{\langle [f_i(t) - \langle f_i(t)\rangle_{av}][f_j(t+\tau) - \langle f_j(t+\tau)\rangle_{av}]\rangle_{av}}{\sqrt{\{\langle [f_i(t)]^2\rangle_{av} - [\langle f_i(t)\rangle_{av}]^2\}\{\langle [f_j(t+\tau)]^2\rangle_{av} - [\langle f_j(t+\tau)\rangle_{av}]^2\}}} \tag{5}$$

where $f_i(t)$ and $f_j(t)$ are time functions whose total energies are finite. The subtractions of the terms $\langle f_i(t)\rangle_{av}$ and $\langle f_j(t+\tau)\rangle_{av}$ in the numerator and $[\langle f_i(t)\rangle_{av}]^2$ and $[\langle f_j(t+\tau)\rangle_{av}]^2$ in the denominator are to remove the effects of constant components. If the error introduced by these components is ignored, the above expression reduces to

$$\rho_{ij}(\tau) \approx \frac{\langle [f_i(t)][f_j(t+\tau)]\rangle_{av}}{\sqrt{\{\langle [f_i(t)]^2\rangle_{av}\}\{\langle [f_j(t+\tau)]^2\rangle_{av}\}}} . \tag{6}$$

If, then, the average power of the traces is made equal,

$$\rho_{ij}(\tau) \approx \frac{\langle [f_i(t)][f_j(t+\tau)]\rangle_{av}}{\langle [f_i(t)]^2\rangle_{av}} . \tag{7}$$

The Analog Seismic Correlator was designed to compute the average of the cross-correlation functions of all possible pairs of a multi-trace seismogram as τ is varied from trace to trace, and to plot percent correlation versus Δt over intervals of geologic interest. The equipment is flexible and may be operated in several modes; but the description here will apply to a split spread, as shown in Figure 3, with N geophone stations either side of the shot and with no geophone at the shot. The total time shift across the seismogram (Δt) is then equal to $2N\tau$. Since the magnetic head spacing across the correlator input magnetic tape is an analog of the geophone station spacing on the ground, it is necessary that the mode of the Δt scanner conform to the mode of shooting. In this analog, the variable t will represent time along the center of the record; and this time will not change as the Δt scanner changes position.

If the seismic signals that are recorded on the magnetic tape are represented by $f_n(t)$, then when they are played back through heads that have been skewed, as indicated in Figure 3, the played back signals may be represented by $f_n(t+n\tau)$. Here n will represent the geophone station number, with $-n$ representing stations to the left of the shot and $+n$ representing stations to the right, and $-N$ and N representing the end stations. If now the signals are added, their sum may be represented by

$$\sum_{n=-N}^{N} f_n(t + n\tau).$$

Squaring, we have the sum-signal $R(\tau)$, whose expansion contains the sum of the squares of the individual signals plus the sum of twice the cross-products of the individual signals. These are the cross-products that are significant in the correlation process. The squares of the individual signals may be removed by squaring each signal and subtracting their sum from the square of the sum-signal. In practice this is done after averaging.

Let the average of $R(\tau)$ be $\overline{R}(\tau)$ over the time interval (T_1-T_2). Then

$$\overline{R}(\tau) = \frac{1}{T_1 - T_2}\int_{T_1}^{T_2} \cdot \left[\sum_{n=-N}^{N} f_n(t + n\tau)\right]^2 dt. \tag{8}$$

And if $P(\tau)$ represents the sum of the squares of the individual signals and $\overline{P}(\tau)$ its average over the time interval (T_1-T_2),

$$\overline{P}(\tau) = \frac{1}{T_1 - T_2}\int_{T_1}^{T_2} \cdot \left\{\sum_{n=-N}^{N} [f_n(t + n\tau)]^2\right\} dt. \tag{9}$$

In the correlator, identical electronic integrators are used to perform the above operations; the limits T_1 and T_2 are set by gating with a dual pre-

set counter; and the integrals are divided by (T_1-T_2) with calibrated gain changers associated with the integrators. The average of the sum of the cross-product terms will then be $\overline{R}(\tau)-\overline{P}(\tau)$.

From equation 6 it is evident that if $f_i(t)$ and $f_j(t)$ are identical for some value of τ, $\rho_{ij}(\tau)$ becomes unity for that value of τ. By making equal the average power of each trace of a multi-trace seismogram of $2N$ traces, it is possible to obtain a close approximation to the normalized multi-trace cross-correlation coefficient $c(\tau)$, where $c(\tau)$ is the average of the cross-correlation coefficients of all the possible pairs. Since there are, in number, $2N(2N-1)/2$ cross-product terms, each of which carries a coefficient 2, and since there are $2N$ terms in the sum of the squared individual traces,

$$(10)\quad c(\tau) \approx \left[\overline{R}(\tau) - \overline{P}(\tau)\right] / \left[(2N-1)\overline{P}(\tau)\right].$$

DESCRIPTION OF OPERATION

The input to the seismic correlator is a drum-type magnetic tape transport with movable heads controlled by a bar that is normally pivoted at the center, as shown in Figure 4. The bar is caused to move about its pivot by a variable-speed motor drive operating a set of cams; this mechanism is called the Δt scanner. In playback, the tape transport is geared to rotate at five times normal speed and makes one revolution in approximately 1.3 seconds. One point is plotted on the correlation curve for every revolution of the drum, each for a different value of τ. The speed of the Δt scanner drive can be varied to plot points at intervals in Δt of $\frac{1}{2}$ to 16 milliseconds. Hence it is possible to scan rapidly in Δt where the correlation is low and then to plot points more closely spaced near correlation peaks.

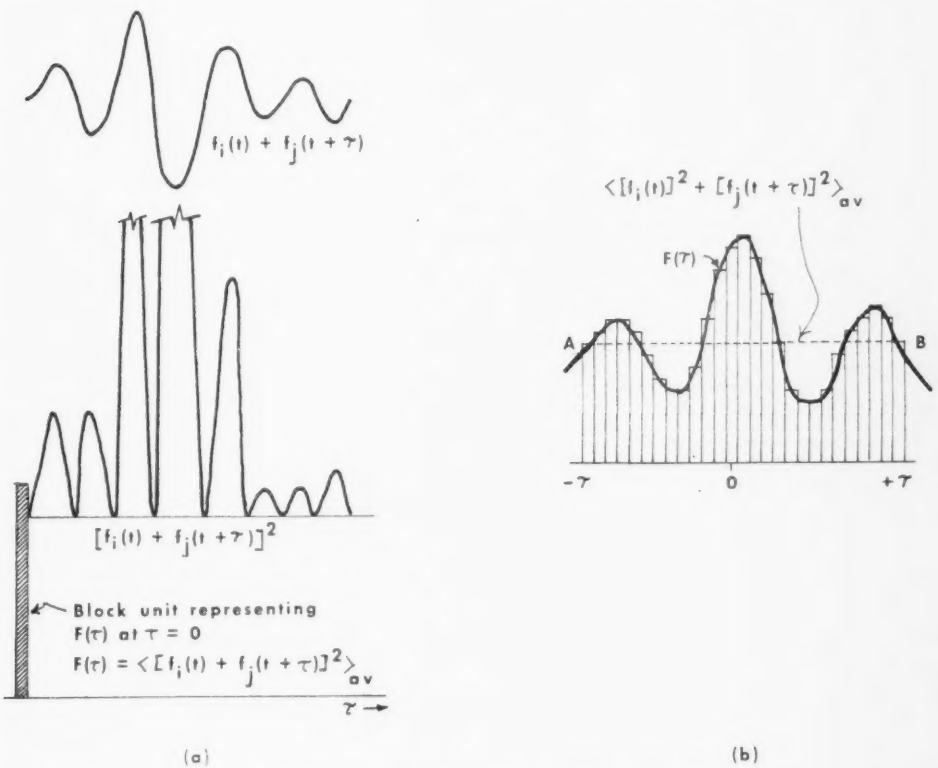

FIG. 2. Maximized sum squared fit of two continuous time functions.

The tape system is of the direct recording type, and the equalization of the playback amplifiers has been designed for the increased tape transport speed. The filters are also of a type suited to the higher frequencies of this type of playback. Each channel has an individual attenuator, and there are ganged attenuators that permit the gain of all channels to be adjusted simultaneously.

After the signals are filtered and their amplitudes are adjusted, they are fed to the two sections of the correlator. In the $\overline{P}(\tau)$ section, the individual traces are squared, added, and passed through a gate to an integrator whose output, the sum of the average powers of the traces over the time interval T_1 to T_2, actuates a meter. In the $\overline{R}(\tau)$ section, the signals are added, squared, and passed through a gate to a second integrator

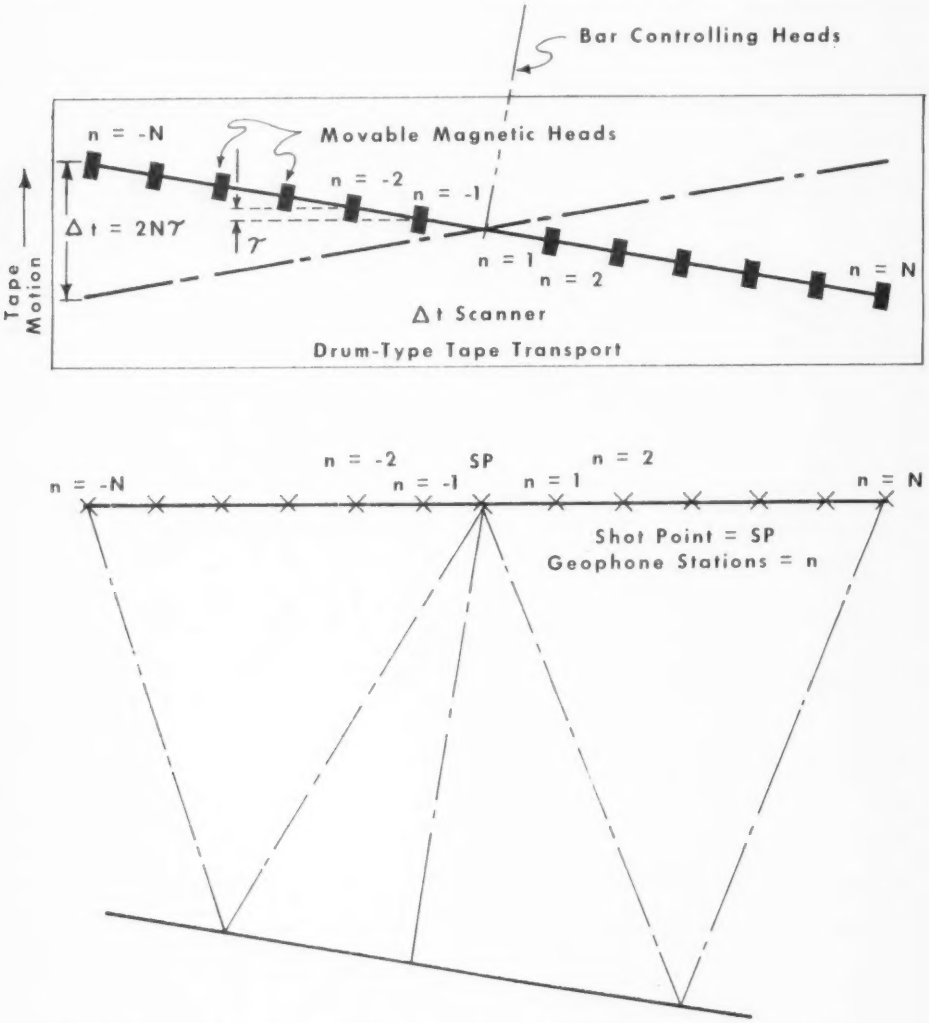

FIG. 3. Diagram of correlator analog where the spacing of the magnetic heads across the tape is an analog of the geophone spacing along the ground.

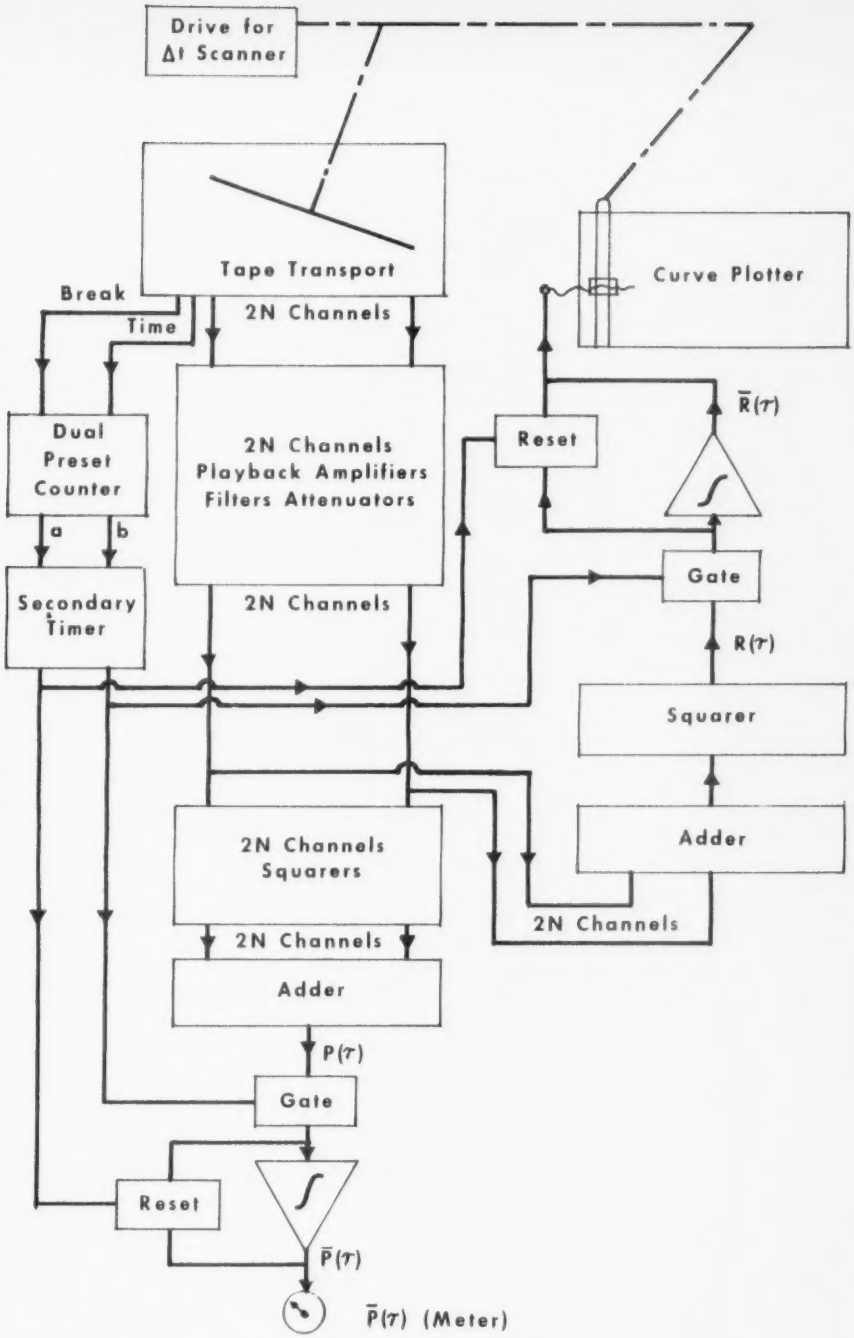

FIG. 4. Block diagram and flow chart of correlator.

whose output is plotted as the correlation function for the time interval T_1 to T_2. After the point is plotted, both integrators are reset and prepared for the next cycle.

The shot break and timing signal control the time interval T_1 to T_2 by means of a dual preset counter. This counter activates a secondary timer at T_2 in order that the plotter may be plotting while the counter is counting the time for the next point.

The average power of the individual channels may be adjusted with the individual channel attenuators; however, since most seismograms are recorded with automatic gain control, this is seldom necessary. The normal procedure is to adjust the ganged attenuator until the meter at the $\overline{P}(\tau)$ output reads a predetermined level. The plotter is calibrated by making its full-scale sensitivity equal to $2N$ times the sum of the average powers of the individual traces; under these conditions, zero correlation will be displaced upward from true zero by the value of the average power. The remainder of the plotter scale will then represent the degree of correlation.

The magnetic tapes for the correlator input are transcribed from field tapes, inserting static and normal moveout corrections. As the Δt scanner operates, it is sometimes necessary to adjust the ganged attenuator to hold $\overline{P}(\tau)$ constant. Only this control and the rate control for the Δt scanner require attention during the plotting of a curve.

EVALUATION

The detection ability of a multi-trace correlator has been analyzed by Faran and Hills (1952). In order to establish limits of dependability of multi-trace correlograms, the work of Rice (1953) has been extended to determine the expected fluctuations of the correlator output for finite samples of 12 random inputs.[1] These results are plotted in Figure 5. For time samples of 0.1 second and a typical seismic spectrum, the standard deviation or the root-mean-square value of the fluctuation of the correlator output should be approximately 5 percent. Thus correlation of 15 percent or three standards of deviation should yield a high degree of reliability. This implies that a seismic event of greater than 15 percent correlation is significant.

In the transition between equations 5 and 6, four terms were dropped to simplify the mathematical operation. This simplification permits a many-fold saving in complex computer equipment, but its effect should be kept in mind by the

[1] The authors are indebted to Dr. M. R. MacPhail, Geophysics Research Section, Humble Oil & Refining Company, for this development.

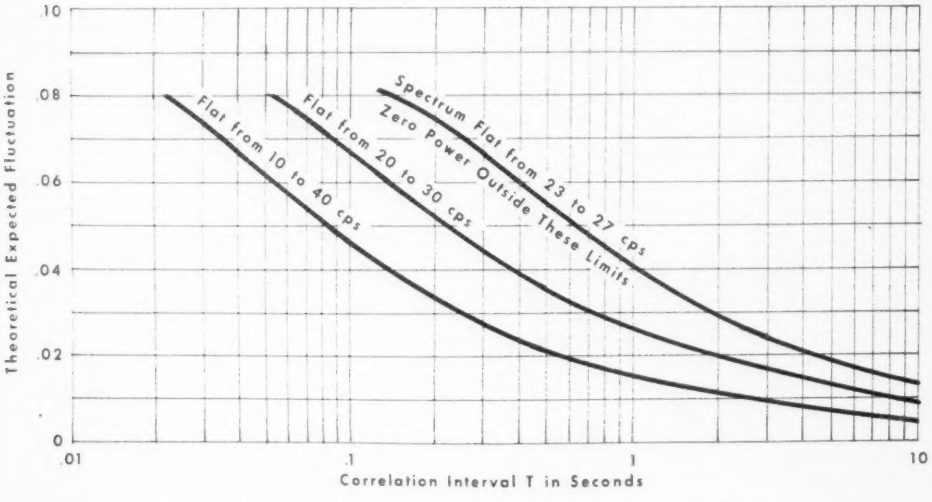

FIG. 5. Standard deviation of correlator output for twelve uncorrelated inputs of length T and power-density spectra as indicated.

operator. For signals of infinite length and no d-c component, the four terms vanish; but as $(T_1 - T_2)$ becomes small, any d-c components created in the gating process may lead to large errors. The expected error caused by neglecting these components will also be governed by the spectrum of the signals. Experimental measurements of groups of 12 seismic signals with a modal frequency of 40 cps indicate that the expected error in correlation is less than 5 percent when a 0.1-second gate is used.

An effort has been made to test the ability of the correlator to detect seismic signals when mixed with random noise and to determine the Δt's of seismic signals that might arrive simultaneously from different directions. In these experiments the message M was an approximation of a Ricker (1940) velocity wavelet with a modal frequency of 50 cps and a breadth of 17 ms. The noise N, when used, was obtained from a random noise generator. In tests in which the message was mixed with noise, the same wavelet was used in each case for message; but it was mixed with different samples of random noise that had been filtered to approximately the frequency spectrum of the wavelet. Many recordings were made, varying the M/N ratio in an effort to determine the threshold of reliable detection. In these tests the peak value of the wavelet was called M and the rms value of the noise was called N. The rms value of the wavelet centered in a 0.1-second gate was measured to be 0.52 of the peak value, and the maximum value of peaks expected in the random noise was five times the rms value of the noise.

It was found that in the above experiment the correlator could follow simulated seismic events with a good degree of reliability where the M/N ratio was unity. To get a statistical evaluation, an 11-tape synthetic continuous profile was recorded with a M/N ratio of unity. The recorded pattern of simulated seismic events included blank-outs similar to those that might be caused by faulting; in all there were 39 synthetic reflections constituting four events. These four events are denoted by the lightly shaded lines in Figure 6. It should be noted that of the 39 synthetic reflections, 36 included the wavelet on all twelve traces of the spread, two on six traces, and one on eight traces. The values of Δt may be observed in Figure 6, which shows also the findings of the correlator. The lightly dotted lines represent data of quality 4 (5–10 percent correlation); the circles with three short dashes on either side represent data of quality 3 (10–15 percent correlation); circles with broken lines on either side represent data of quality 2 (15–20 percent correlation); and the circles with solid lines represent data of quality 1 (20 percent or greater correlation). Circles are used to represent the time of a correlator response referred to the center trace of a given spread. Closed circles (dots) represent correlator response which correctly designates the presence of signal; and open circles, correlator response when no signal is present. An event between 0.940 and 1.040 seconds on record 5 correlated 29 percent, the highest correlation value observed, for which the oscillogram and the correlation curve are shown in Figure 7.

The correlator responses to the noise traces containing the 39 synthetic reflections are tabulated below:

Correlator Response		*Synthetic Reflections Observed*	*Spurious Responses (No Reflection Present)*
Grade 1	>20%	18	2
Grade 2	15–20%	10	25
Grade 3	10–15%	6	81
Grade 4	5–10%	5	379
No response		—	—
		39	487

The resolving power of a multi-trace correlator to two signals from separate sources has been analyzed by D. C. Fakley (1959). The Δt of two wavelet-type signals can usually be resolved visually unless there is an excess of noise or unless two events arrive at the same time. As the Δt's of the two events approach the same value in the latter case, the eye loses its ability to resolve them; but the point has not been established where resolution ceases. This is true also with the correlator to a lesser extent, and the following test was devised to determine the conditions for dependable resolution.

For this test, two sets of wavelets with the same t but with different Δt's and amplitudes were recorded and processed with the correlator. In this case the wavelets had a breadth of 17 ms and a model frequency of 50 cps. One of the events had a Δt of zero and the other a Δt of -22 ms. These signals were processed by the correlator and gave the curve shown in Figure 8a; here the correlation curve peaked at $+5$

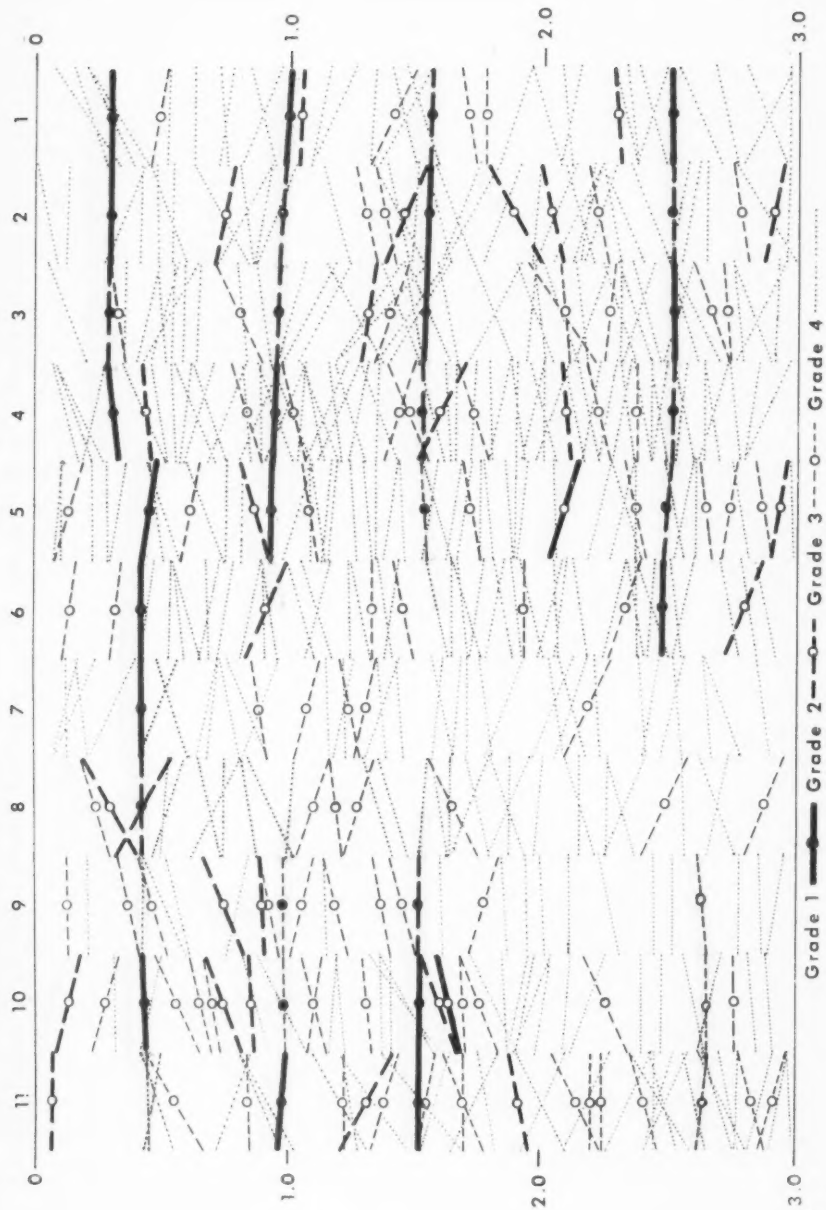

FIG. 6. Graded cross-section of synthetic seismic signals mixed with random noise.

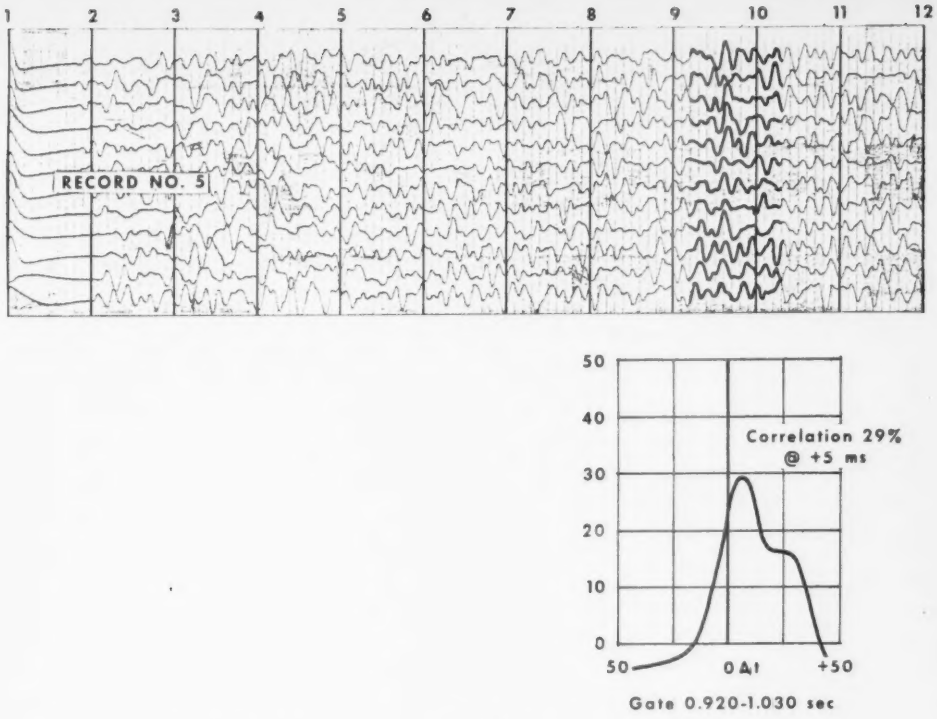

FIG. 7. Correlation curve and oscillogram of strongest event on section.

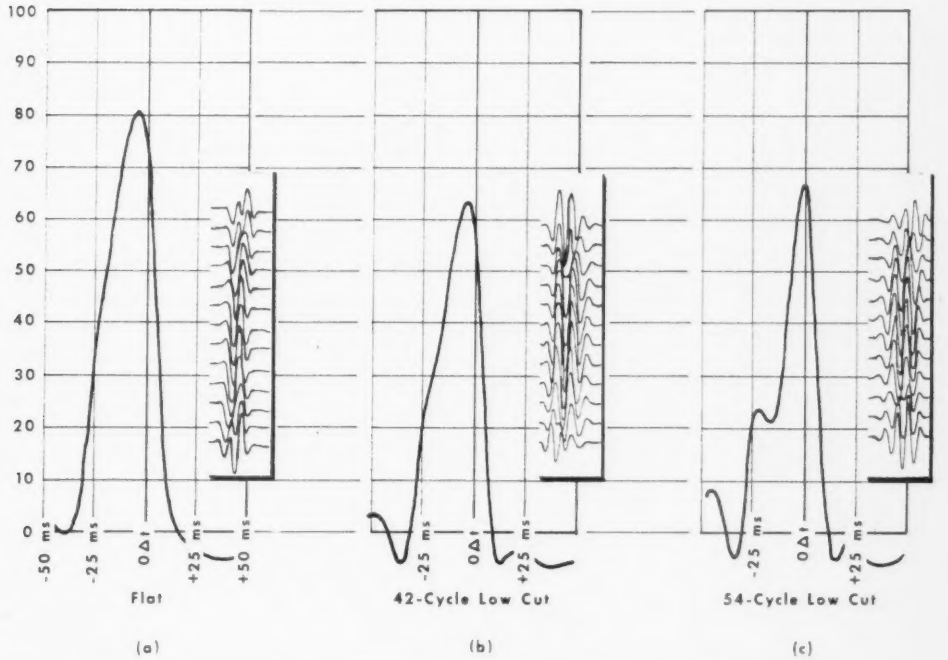

FIG. 8. The detection of simultaneous arrivals by the correlator with the aid of low-cut filters.

ms Δt with no indication that there might be two separate events. By using low-cut filters, the two events could be separated with the proper Δt, and the ratio of the peaks indicated the relative amplitude of the two events. The events were resolved by removing the frequency components with periods greater than the difference in Δt of the two events. Figure 8b is the correlation curve for the signals when they had been passed through a filter that removed the frequencies below 42 cycles; for Figure 8c a 54-cycle low cut was used.

PROCESSING FIELD DATA

When field data are processed with the correlator, special transcriptions of the data are made with low-velocity and normal moveout corrections. Correlation curves are made to cover the zones of interest, and from these curves the Δt's and quality are tabulated. These curves may be used to plot a phantom horizon or to aid in tabulating event times from the seismic section. Where time picks are made, the events are plotted on a graded time cross-section, and from this cross-section the time ties of the events are judged. Much random material may thereby be discarded.

Because the correlation process involves transcription, addition, multiplication, and integration, it is only natural that the correlator equipment should be used for other types of seismic data analysis. Auto-correlation functions have been computed and plotted by recording the same information in two separate tape channels and cross-correlating the two channels. The auto-correlation function is plotted as a curve on the strip-chart recorder, and these curves have been studied in an effort to gain a better understanding of seismic wave forms. Some of the auto-correlation functions have been recorded on magnetic tape and correlated with cosine waves of different frequencies to produce the power-density spectrum of the seismic trace. The coefficients and phase of the frequency components of seismic traces have been computed by cross-correlating sine and cosine waves of the various frequencies with the seismic traces.

CONCLUSIONS

The correlator can be used to an advantage to retrieve the seismic message when the message-to-noise ratio is low and to identify separate events with different Δt's but essentially simultaneous arrival times. As a result, a better understanding of many types of geologic structures may be obtained from the seismic data. Since geologic zones of interest are usually represented by signals that have short time duration, the computer instrumental error is less than the expected error caused by the statistical limitation of the short sample. The process described here is slow; but even in its present state, the Analog Seismic Correlator will process a sample of a seismic record in one to ten minutes. The computation time will vary with the number of points needed to outline the correlation curve.

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GEOPHYSICS, VOL. XXVI, NO. 3 (JUNE, 1961), PP. 309-319, 5 FIGS.

AN EVALUATION OF BASEMENT DEPTH DETERMINATIONS FROM AIRBORNE MAGNETOMETER DATA*

PETER JACOBSEN, JR.†

Abstract: Four years ago Creole Petroleum Corporation submitted identical airborne magnetometer data for a portion of the Eastern Venezuela basin to two different geophysical contractors for independent, detailed analysis. These contractors offer the customary generalized basement depth maps; but they specialize in delineating areas of relatively local relief on the basement surface. Both kinds of interpretation were requested by Creole. The main purpose of the study was to evaluate the reliability of interpretations of local basement relief from magnetic data. Accordingly, the region for study was deliberately chosen to include, in part, areas for which Creole had considerable knowledge of basement depths and local basement configuration from other sources. Local basement relief shown by the two magnetic interpretations is in poor agreement with basement depth information from seismograph and well data. Moreover, the two magnetic pictures bear little resemblance one to the other. With respect to regional basement depth contours, one of the magnetic interpretations compares statisfactorily with the picture based on seismograph and well control. A tentative conclusion is that local basement relief cannot be reliably interpreted from magnetometer data alone.

INTRODUCTION

Over the years, two broad schools of thought have evolved in the petroleum industry concerning the degree of geological interpretation which should be attempted from magnetometer data. Many exploration people feel that magnetic interpretations should be mostly qualitative. Such interpretations usually do not go beyond generalized basement depth maps which depend on analysis of the relatively large anomalies (the so-called intrabasement type) due to magnetic inhomogeneities within the basement rocks themselves. Among others, the Creole Petroleum Corporation of Venezuela and a number of other Standard Oil Company of New Jersey affiliates have taken this approach to the utilization of magnetic data.

In contrast, more rigorous mathematical analysis of magnetometer results and more detailed geological interpretation have been practiced elsewhere in the petroleum industry. The Gulf Oil Corporation, various other oil companies, and, most particularly, several geophysical contractors are widely reported to have successfully carried their studies of magnetic data a good deal further to include detection of local relief on the basement surface. For these more quantitative interpretations, the ordinarily much smaller, so-named suprabasement anomalies associated with local basement relief are studied, usually with the aid of second derivative maps.

Creole Petroleum Corporation and other Jersey companies became increasingly interested in obtaining a more complete evaluation of the detailed interpretation techniques. In 1955 Creole obtained airborne magnetometer coverage in northeastern Venezuela which seemed ideal for such an evaluation. The following year the company submitted identical basic data from a portion of the Eastern Venezuela survey to two different geophysical contractors. These contractors offer the customary generalized basement depth maps, but they specialize in delineating areas of relatively local relief on the basement surface. Creole requested both kinds of interpretation.

AREA AND PROCEDURES FOR THE MAGNETIC INTERPRETATION

The location of the area of this study is shown in Figure 1. Geologically, the area is situated on the gentle south limb of the Eastern Venezuela

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† Creole Petroleum Corporation, Caracas, Venezuela. Now with Jersey Production Research Company, Tulsa, Oklahoma.

FIG. 1. Index map of Venezuela showing area of study.

Tertiary basin. The approximate limits of this basin are indicated in Figure 1. The block of airborne magnetometer coverage was deliberately chosen to include, in part, areas in which basement depths were rather well known from extensive seismograph and well control. It also took in deeper parts of the basin where no wells have been drilled and where little exploration work of any kind had been done at the time. The surface area of the study is approximately 3,500 square miles.

The survey from which the present data were selected is probably the most detailed airborne magnetometer work done to date for the oil industry in Venezuela. Spacing between flight-lines averages one and one-half miles, diurnal control was flown at six-mile intervals or better, and horizontal positioning was by Shoran. The standard Gulf-type instrument was used. The area was flown at an elevation of 2,000 ft above sea level. Most of the flight-lines for the southern half of the area were inadvertently oriented in an east-west direction, more or less parallel to the known structural trends and to the expected magnetic grain. Both contractors emphasized that north-south lines would have been preferable as their procedures often include minute examination of the actual magnetometer tapes for evidence of low-magnitude anomalies. However, neither regarded the unfavorable orientation of part of the flight-lines as a serious obstacle to their interpretations.

Depths to basement and bottom-sample material for three wells were given to the contractors. Creole supplied no other exploration data on the area. Some geological information on the southern part was available in the literature (Bucher,

1952; Mencher, et al, 1953). For the balance of the area, inferences as to the regional configuration of the basement surface and the general structural characteristics could be drawn from published data on adjoining regions to the west (Hedberg, et al, 1947).

Both contractors prepared second derivative maps with the aid of electronic computers. Each used some variation of the "two-ring" method to obtain second derivative values. The dimensions of the rings were approximately the same in both cases, but the grid on which the derivative values were calculated was quite different. For the first interpretation to be presented, the grid was slightly over twice as large as for the second one. The two procedures for calculating the second derivative values probably gave about the same emphasis to local magnetic anomalies of a given areal extent. However, the derivative contouring for the first interpretation was based on less than half as many control points as were used in the second. The second derivative contours are omitted here because such maps are not too meaningful in themselves to any but specialists in the field.

The contractors did not necessarily give a complete description of the techniques used in analyzing the magnetic anomalies. Both apparently worked with the total magnetic intensity as well as the second derivative maps. It is understood that procedures published by Vacquier, et al (1951) were mainly used in calculating depths from the total intensity anomalies. For both studies, the mineralogy of the bottom-hole material was examined in detail and magnetic susceptibility measurements were made on the samples as a further aid to the interpretations.

The geological results were presented in the form of generalized basement depth contour maps. Interpreted trends or areas of local relief on the basement surface were superimposed on those maps, but usually no attempt was made to express these smaller features in the regional contouring.

EVALUATION OF THE MAGNETIC INTERPRETATIONS

The corrected total magnetic intensity picture for the area is shown in Figure 2. Certain geographical information is included on this and on succeeding figures for further orientation. The Maturín-Barrancas highway traverses the area from northwest to southeast. The study is bounded roughly on the north by the Guanipa River and on the east by the Mánamo River which is seen in the extreme northeast part of the map. Locations and names are given for the three control wells aforementioned.

Geologically, the area of study includes the well-known Jobo-Temblador-Pilón fault system which trends east-northeast through the southern part. The map takes in just the extreme eastern portion of the major Greater Oficina producing region.

One of the magnetic interpretations (here designated Interpretation A) is presented as Figure 3; the other (Interpretation B), based on precisely the same data, is given in Figure 4. For comparison, Figure 5 shows basement depth contours based on seismograph and well information. The contour interval for Figures 3, 4, and 5 is 1,000 ft, the same interval used on the contractors' original larger-scale maps.

Turning closer attention first to Figure 5, the subsurface geology for the southern part of the area was already known in some detail at the time of the magnetometer work. Since then, Creole-interest and Creole wholly-owned seismograph surveys have extended the control well to the north to include much of the present area. A distinctive and persistent "Basement" reflection is widely recorded in this part of the Eastern Venezuela basin. The stratigraphic position of this reflector is established beyond any reasonable doubt in the southern part, where velocity control is available from a number of wells bottomed in or just above the basement rocks; and there is every reason to believe that the "Basement" reflection is also a good guide to basement depths farther basinward, beyond the well control.

Contours on the basement surface, and structure within the overlying sediments as well, show remarkably uniform north dip of three to eight degrees, interrupted only by a number of major strike faults with displacements on the order of 500–1,000 ft. For present purposes the fault picture has been greatly simplified to show only the pertinent larger features. However, even in the areas of most concentrated drilling and shooting, practically no cases of structural reversal, either local or regional, are known at the level of the "Basement" reflection. The quality of the reflection data does deteriorate toward the northern portion of the area with increasing depth to the

(*Continued on page 316*)

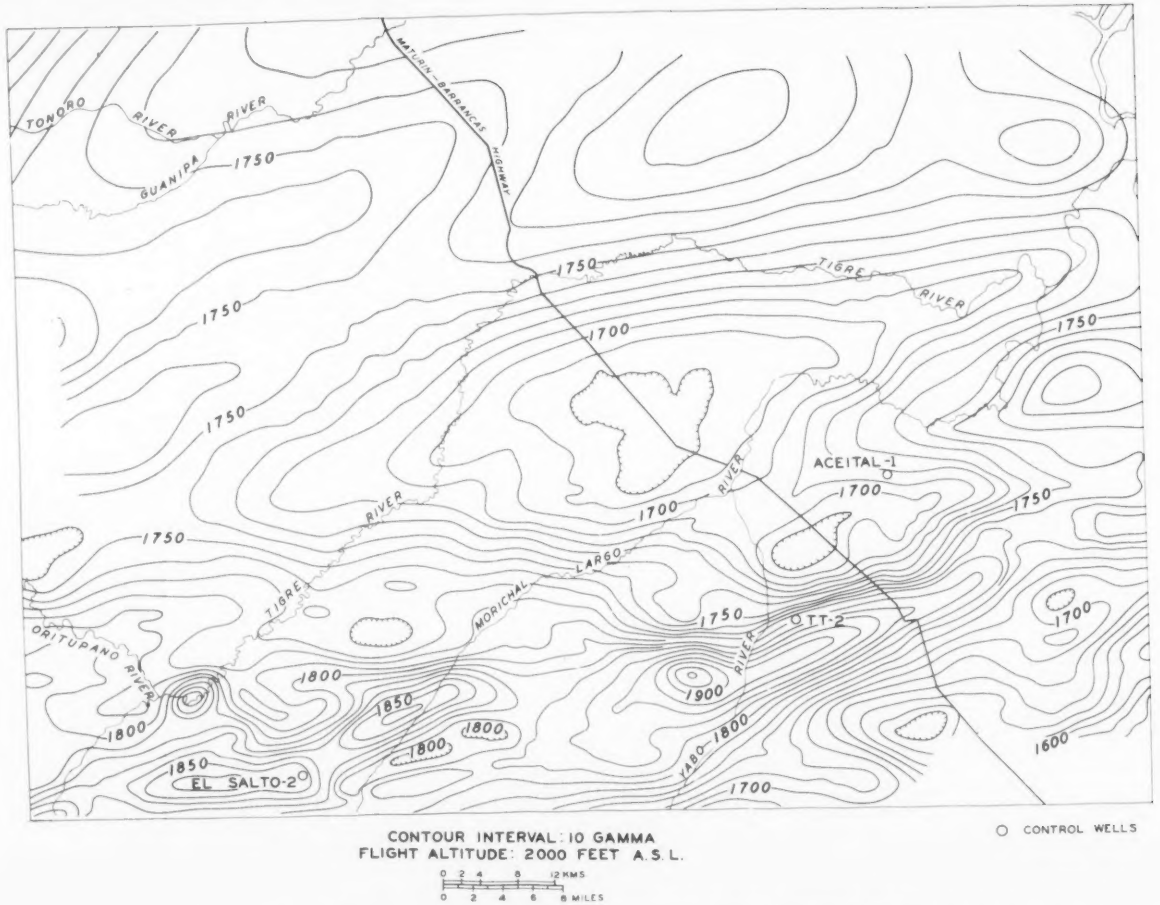

FIG. 2. Total magnetic intensity map for portion of Eastern Venezuela basin.

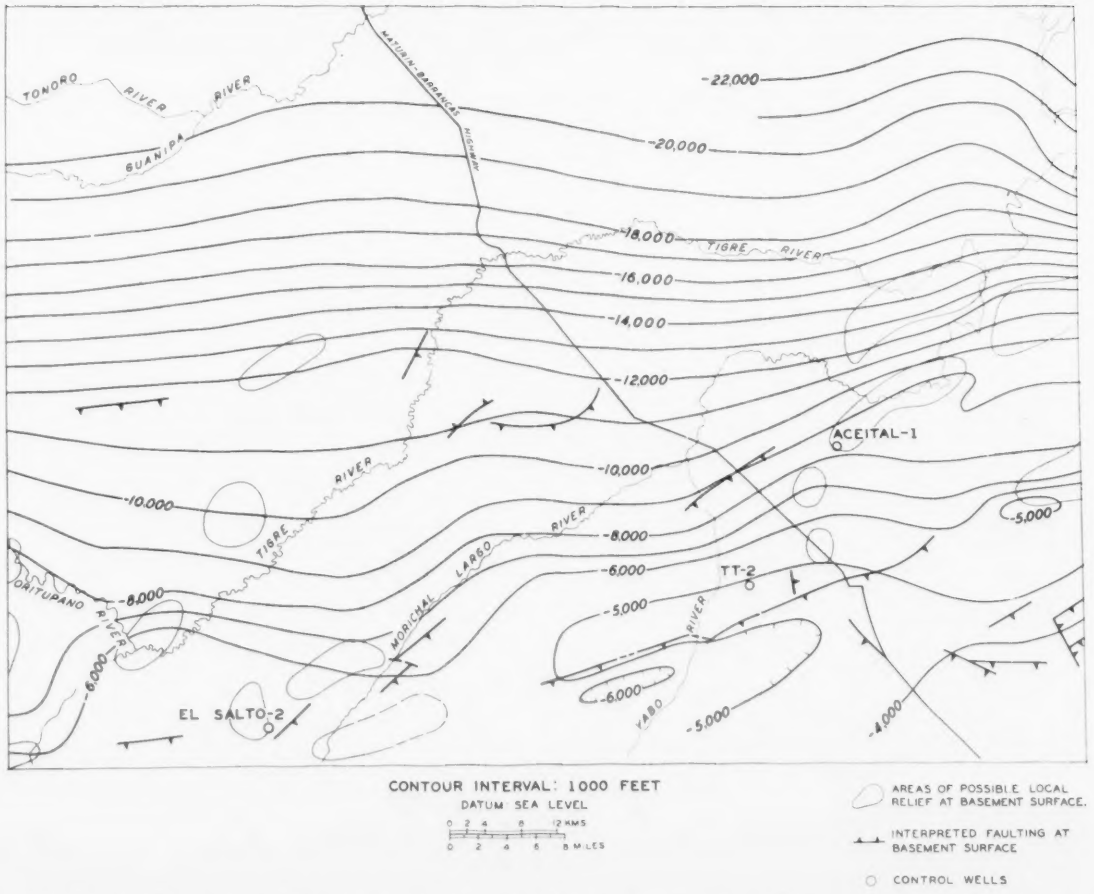

FIG. 3. Airborne magnetometer interpretation (A) for portion of Eastern Venezuela basin. Contours are generalized basement depths. Areas of possible local relief on basement surface and interpreted faulting at basement levels are also shown.

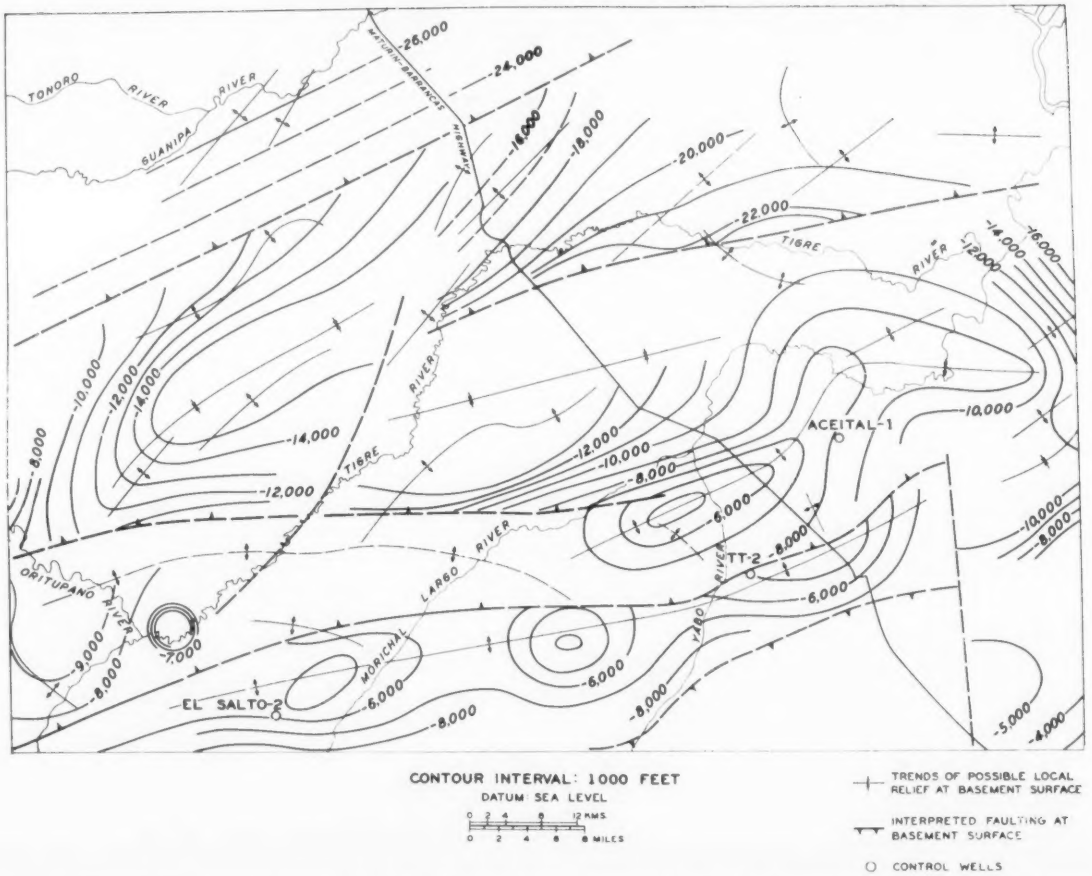

FIG. 4. Airborne magnetometer interpretation (B), for same area as Figure 3. Contours are generalized basement depths. Trends of possible local relief at basement surface and interpreted faulting at basement levels are also shown.

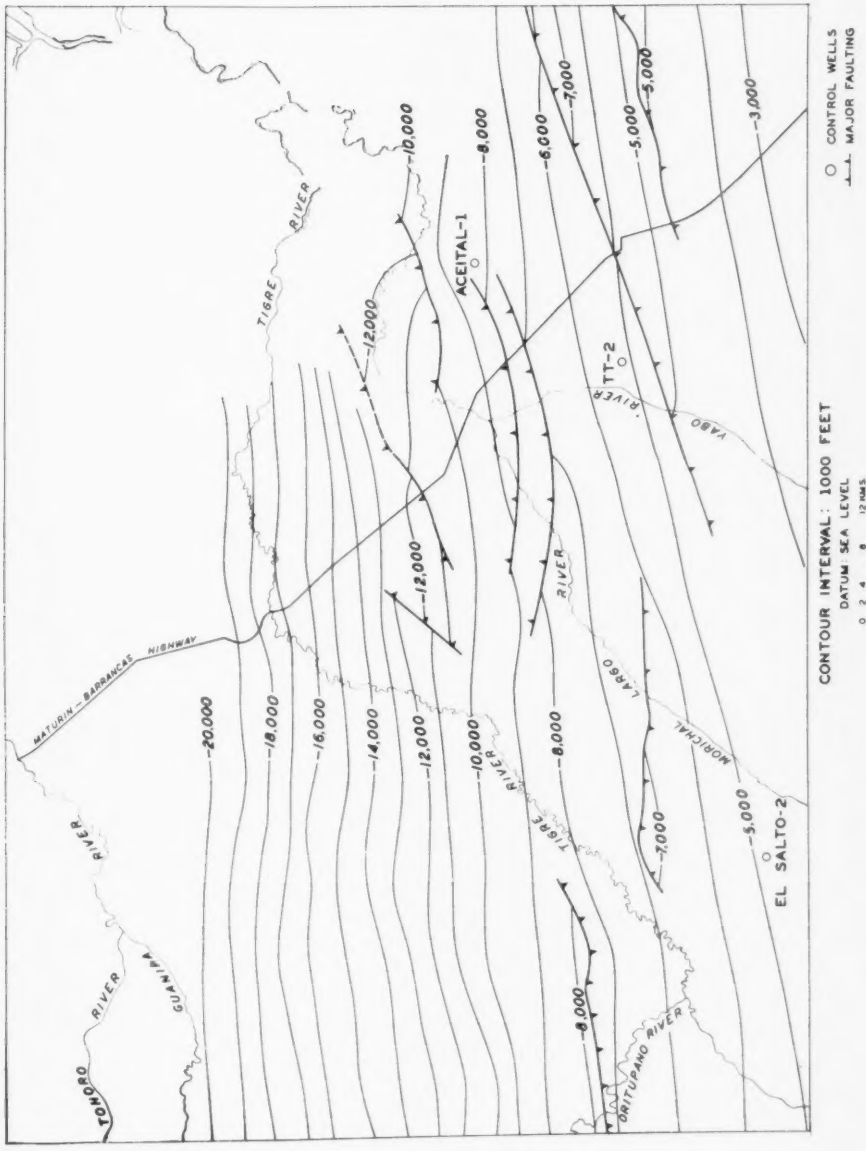

FIG. 5. Generalized basement depth map and major faulting for portion of Eastern Venezuela basin, based on subsurface and seismograph control. Area is the same as that for Figures 2, 3, and 4.

key reflector, and some sizeable faulting may have been missed; but the possibility of any appreciable areas of south dip is considered remote.

Returning to Interpretation (A) in Figure 3, the regional basement configuration and depths calculated from magnetic data are in good agreement with those shown in Figure 5. With regard to local anomalies at the basement surface, the correspondence between the two maps is poor. The two east-west faults extending west from control well Aceital-1, taken together, represent the major structural anomaly of the area of this study. The magnetometer interpretation gives little hint of these features. Figure 3 actually suggests more anomalous conditions along the eastward extension of this fault trend; but, in fact, the two faults are thought to die out rapidly in that direction. The major east-northeast-trending fault in the southeastern part of the area may not represent a completely independent interpretation of the magnetic data, as the contractor may have been guided in part, and rightly so, by published information on this Temblador fault system.

Close seismograph and well control over most of the areas for which possible local relief on the basement surface is interpreted practically eliminates the possibility that any appreciable anomalies are actually present in those areas.

Interpretation (B) (Figure 4) bears little resemblance to Interpretation (A). It is also in poor agreement with Figure 5, both regionally and locally. The regional configuration interpreted for the basement surface is radically different from the monoclinal north dip probably present throughout the area of this study. The contractor shows regional south dip over considerable areas whereas south dip of any magnitude or areal extent is virtually ruled out for much of the region by other exploration data. In many parts of the area, interpreted depths to basement are at variance by thousands of feet with those shown in Figure 5.

It is of passing interest that the regional high and low trends of this interpretation agree approximately with the major maxima and minima of the total magnetic intensity map.

The correspondence between trends or areas of local basement relief on Figures 4 and 5 is also poor. An extreme example is the plug-like intrusion (?) interpreted in the southwestern part of the area. None of the numerous lesser structural reversals shown in Figure 4 correspond to any known local structure at basement levels. With respect to faulting, the trends shown by the contractor in the southern half of the area are often roughly parallel to known faults. In some cases the positions are quite similar, but the directions of displacement are rarely in agreement. The east-northeast-trending, down-to-basin fault in the northwestern part of the map, with up to two miles of throw, gets no support from the considerable seismograph coverage now available in that area. From discussions with the authors of Interpretation (B), we have the impression that they took little account of published information on the southeastern part of the area.

CONCLUSIONS

The tentative conclusions from the foregoing studies are the following:

(1) In proper hands, careful analysis of intrabasement-type magnetic anomalies may yield a reliable and useful generalized basement depth map.

(2) Local basement relief based on a study of the usually smaller, suprabasement magnetic anomalies cannot be reliably interpreted from magnetometer work alone.

It is recognized that the different approaches to interpretation of magnetic data cannot be categorically evaluated based on the present results alone. The magnetic characteristics of the basement rocks, the kind and magnitude of relief on the basement surface, and other geological conditions might be more favorable in one area than another. The fact that two experienced contractors working with precisely the same data should turn out such different interpretations, particularly of local basement relief, is perhaps most significant. This suggests either that the techniques used for analyzing the magnetic data are inadequate or that such detailed interpretation is beyond the resolving power of magnetometer surveys.

The foregoing observations are by no means intended as a wholesale indictment of magnetometer work, and the present results do not necessarily condemn close mathematical and physical analyses of individual magnetic anomalies. Further, it is not the purpose of this paper to question the integrity or reject the particular methods of the reputable contractors who made these studies. At the same time, this factual account of Creole's experience with detailed magnetic interpretations may help other exploration people to a more prudent use of magnetometer data in oil exploration.

ACKNOWLEDGMENTS

Mene Grande Oil Company and Compañía Shell de Venezuela, Ltd., co-owners with Creole of the basic magnetometer data used in the present study, generously agreed to disclosure of these results. The southern portion of the generalized basement depth map is based in considerable part on seismograph and well data from joint Creole-Mene Grande operations. Mene Grande has kindly given its permission to publish this information in the present form. Acknowledgment is also made to Phillips Petroleum Company for the release of certain seismograph data. The basement picture in the central portion of the area, and to a lesser extent that in the extreme southwestern part, is derived from a Phillips-Creole joint-interest survey and from Phillips exchange lines.

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DISCUSSIONS OF "AN EVALUATION OF BASEMENT DEPTH DETERMINATIONS FROM AIRBORNE MAGNETOMETER DATA," BY PETER JACOBSEN, JR.

In his discussion of the magnetic interpretations, Mr. Jacobsen rightly distinguishes between the determination of basement depth and configuration by analysis of anomalies originating from magnetization contrast within the basement and the delineation of local relief or faulting at the basement surface by analysis of smaller anomaly trends. It cannot be emphasized too strongly that the principal purpose of conducting aeromagnetic surveys is to outline the extent and depth of sedimentary basins, and the calculation of depth to basement by quantitative analysis of anomalies has progressed to the point where reliable results can be obtained by skilled interpreters. Considering only the contour maps of the basement surface shown by the two interpretations, Mr. Jacobsen's first conclusion is well taken; one of the contour maps (Interpretation A) is excellent, and in view of the simplifying assumptions that must be made as to the shape of intrabasement magnetization contrasts in order to obtain estimates of depth, any magnetic interpreter would be extremely gratified if all his basement contour maps checked as well as this one with data obtained subsequently by seismic surveys or by drilling. The greatest difference between the contours shown on Interpretation A and the contours based on subsurface and seismograph control is 2,000 ft, and the average error seems to be about 700 or 800 ft; considering that the basement depth increases to more than 20,000 ft in the northern part of the region, it is unlikely that this interpretation could be improved upon.

The basement contour map shown on Interpretation B is an entirely different matter. Errors in depth of the order of 6,000 ft can be found, and it is astonishing that the detailed structural configuration of the basement could have ever been derived from the magnetic intensity map. It is interpretations like this, where one has attempted to obtain more from magnetic data than is warranted, that makes it often so difficult to convince exploration management that sound results can be obtained from magnetic surveys.

This leads us to the subject of areas or trends of possible local relief at the basement surface shown on the interpretation maps. It seems that certain contractors may be at fault for emphasizing this aspect of interpretation too much. Small anomalies which are attributed to basement relief or faults could also be caused by local concentrations of magnetic material within the basement, and in the absence of any other information, the exact source cannot be determined. So it should not be surprising if the anomalies have no structural significance; however, since they might be related to basement relief, the practice of outlining the areas or trends probably should not be discouraged. It seems that the degree to which the anomalies are emphasized is the principal consideration. For example, if a survey of a basin covers known anticlines or faults and these are associated with anomalies, similar types of anomalies in regions where the structure is unknown would deserve much greater consideration than anomalies selected solely on the basis of their form and magnitude.

R. J. BEAN
Shell Oil Company
Los Angeles, California

The conclusions reached by Mr. Jacobsen are in some ways the most significant part of his paper.

"(1) In proper hands, careful analysis of intrabasement-type magnetic anomalies may yield a reliable and useful generalized basement depth map.

(2) Local basement relief, based on a study of the usually smaller, suprabasement magnetic anomalies, cannot be reliably interpreted from magnetometer work alone.

It is recognized that the different approaches to interpretation of magnetic data cannot be categorically evaluated based on the present results alone. The magnetic characteristics of the basement rocks, the kind and magnitude of relief on the basement surface, and other geological conditions might be more favorable in one area than another."

At this point, I would terminate the conclusions.

My first reaction to the basic data is that the spacing of the profile lines should not be greater than one mile apart and, of prime importance, these lines should have been flown perpendicular to the strike of the basin and structural features. I would regard the east-west flight lines a very serious obstacle to the interpretation of faults with an east-west strike!

The approach to the interpretation of aeromagnetic data is somewhat controversial, but I would prefer to use the total intensity contour maps to make a generalized basement relief map from depth estimates on each of the magnetic anomalies and include significant probable faulting. Beyond this point, the magnetic data do not have unique solutions and an interpreter can only suggest the probability of suprabasement topography. Therefore, such anomalies that the interpreter selects from a second derivative map can only be considered as possible local basement topographic relief, which would require other means of exploration for confirmation.

Let us compare Figures 3 and 4. Based on the contoured total intensity anomalies, there are approximately twelve anomalies from which depth estimates can be made and five steep gradient slopes which are characteristic of faulting or sharp relief. Figure 3 makes the better use of these data by presenting a geologically feasible contour map. Using this map for reconnaissance in exploring the area, I would be pleased to find 90 percent accuracy after detailing the area. Figure 4 is incomplete and yet much too complicated to have been derived from the basic data alone. Such a desperate attempt to detail local basement relief is detrimental to the contractors and casts doubts on this reconnaissance tool which can be valuable in establishing exploratory programs in new sedimentary basins.

WALTER R. FILLIPPONE
Union Oil Company of California

1. The paper presents an adept and timely study of the reliability of magnetic interpretation. While there is not enough information given to enable the reader to judge the accuracy of all of the author's statements, there is little doubt that the study has been methodical and objective and we are inclined to accept the explanations offered.
2. The author concludes that a generalized basement depth map can be produced "in proper hands." This qualification is certainly justified in view of the gross discrepancies between Interpretations A and B. Moreover it draws attention to the subjective nature of even the most elementary stages of magnetic interpretation. This has been said many times in the literature (e.g. Skeels, Nettleton etc.) and cannot be overemphasized.

   It is our belief that this subjectivity need not be a serious limitation to the method, and is actually one of its most powerful tools. A proper interpretation requires the formulation of geological concepts concurrently with the solution of magnetic anomalies; only by this process can a reasonable geological picture of the magnetic basement be derived.

   The interpreter's experience (particularly in areas of exposed "basement") guides the exercise of subjective criteria and ensures a reasonable and consistent geological solution. Wild and unreasonable magnetic interpretations are invariably the result of muddled or incautious geological thinking. Careful application of mathematics within well-understood physical and geological assumptions, followed by successive modifications and improvements, not only arrives at the most reasonable basement depth map but at the same time develops a geological picture of the basement which is essential in the next stage—the interpretation of structure and local basement relief.
3. The author's second conclusion is worded in such a way that one can neither agree nor disagree with it. He is saying, in fact, that an interpretation based on magnetic anomalies cannot be done from magnetic work! However, we get the gist of his argument and are completely in agreement.

   Firstly, local relief can only produce magnetic anomalies when the basement is fairly magnetic. This implies that local relief can only be seen in the vicinity of intra-basement magnetic anomalies. However, anyone familiar with Precambrian geology knows that it is the more acid rock types that form most of the topographic highs. To derive local relief by a study of magnetic anomalies is to imply that relief occurs only in the areas of basic rock.

   Secondly, we do not believe, nor have we found in our work, that one is able to separate reliably the effect of local relief from that of intra-basement magnetic inhomogeneities. To ascribe the residual magnetic effect after subtraction of the anomaly from a simple, homogeneous geometric form to local relief is inconsistent with geological fact.

   Finally, the author implies that studies leading to interpretation of local relief are more "quantitative" than those aimed at generalized basement depth. This depends on the approach. We prefer to base any predictions of local relief on a study of lithological and structural changes and their relation with known and/or generalized relief. These studies are often aided by analytically derived maps, such as the second derivative, since these bring out grain and "character" differences not always visible

in the total intensity maps; but essentially they are based on qualitative considerations.

4. By separating the different schools of magnetic interpretation into two camps, the author has oversimplified the problem. There are as many camps as there are geophysicists. It is often difficult to get agreement on method even within one organization; in fact it is usually simpler to arrive at a common solution to a magnetic problem than to agree on a method of solving it.
5. In all fairness to Interpreters A and B, particularly the latter, credit should be given for imaginative thinking. By qualifying areas of interpreted local relief as "possible," they cannot be accused of misleading their clients. Data so qualified should always be treated as speculative, the degree of which is commonly stated in the report.

   Our argument is not whether such inference should be drawn and shown but only in the method of drawing the inference. We do not believe that a survey can be over-interpreted. Such extra interpretation can often generate new ideas and alternative concepts which, however speculative, may be of extreme value to the exploration geologist. If all such concepts are treated in their proper perspective, it only requires the odd correct one to offset the many that may be the purest fantasy.
6. Figures 3 and 4 should show the locations of all of the calculated basement depths. The reader cannot judge the amount of actual control used in the basement contouring and to what extent the interpreter was using qualitative reasoning or intuition.
7. The locations of wells to basement and seismic basement control should likewise be shown in Figure 5. One cannot, for example, rule out Interpreter B's mountain at the junction of the Oritupano and Tigre rivers unless seismic or well control exists immediately over it (though we have to admit that it is highly unlikely).

NORMAN R. PATERSON
Hunting Survey Corp., Ltd.,
Toronto, Ont., Canada

Except for some minor discrepancies and inconsistencies, I agree, in general, with the conclusions listed in Jacobsen's article.

The analysis of hundreds of thousands of linear miles of aeromagnetic traverses has forced me to conclude that the magnetic detection of basement topography of *moderate* relief is virtually impossible. I believe that this conclusion is particularly valid for basin areas where the sedimentary column is quite thick.

On the other hand, the consensus of opinion among magneticians is that it *is* valid to prepare regional contour maps of the basement surface from aeromagnetic data. The U. S. Geological Survey has made available to the public two such maps of the Precambrian surface based on an analysis of aeromagnetic data alone. One of these covers a large area in northeast New Mexico while the other covers the entire state of Indiana. For both maps, contours were generalized and an accuracy of approximately 15 percent or better is claimed. Since the publications of the Indiana basement map, several confirmations of the depth estimates have been received from both the state and from exploration geophysical companies.

To compute basement relief from aeromagnetic data the lithology and physical properties of the basement rocks must be known in considerable detail. With an adequate sampling of the rocks for magnetic susceptibility and perm, it is possible to estimate basement topography.

The map presented by contractor, A, is in good agreement with the known basement topography, although other interpreters might have produced still more reliable maps. It is often possible to predict rock contacts of different lithologies, but it is dangerous to predict the location of faults, except in areas where they may be predicted as extensions of known faults. Contractor A has fallen into the trap of indicating isolated faults which perhaps should be properly classified as contacts.

The fact that interpreter, A, has incorrectly suggested "possible local relief of basement surface" by outlining selected areas, is *not* an indictment either of his method or of his interpretive ability. The client must understand that, although the odds for prediction of local structures were unfavorable, interpreter A, had no alternative but to suggest the existence of these inferred topographic highs. Further investigation of these areas for possible petroleum potential must be left to the chief geologist and the exploration manager. On the other hand, the interpretation presented by contractor, B, is undeniably incorrect even in a regional sense.

To reiterate, I do not believe that in most petroliferous areas it is possible to determine detailed basement topography from aeromagnetic data. Fortunately, except for a handful of star-gazing enthusiasts, most magneticians engaged in this art, concur. The sort of adventure attempted by contractor B, is similar to the circumstances that forced the science of geophysics to take a step backward many years ago. I hope that this will not happen again.

The title of the paper is misleading if not incorrect. In the abstract, the statement is made that "the main purpose of the study was to evaluate the reliability of interpretations of local basement relief from magnetic data." This is surely inconsistent with the title of Jacobsen's paper "An Evaluation of Basement Depth Determinations From Airborne Magnetometer Data."

ISIDORE ZIETZ, Chief
Regional Geophysics Branch
USGS
Washington, D. C.

GEOPHYSICS, VOL. XXVI, NO. 3 (JUNE, 1961), PP. 320–341, 14 FIGS.

SALT BED IDENTIFICATION FROM UNFOCUSED RESISTIVITY LOGS*

J. R. LISHMAN†

Abstract: Salt beds have almost infinite electrical resistivity. They differ from other infinitely resistive beds in that they are usually soluble in drilling fluids, and give rise to enlarged boreholes. An infinitely resistive bed lying between shales may be recognized from the characteristic shape of the electric log resistivity curves, and the ratios of their readings. Any one of the curves may then be used to compute the borehole diameter, and hence decide whether the bed is salt.

Where a washed out salt bed is adjacent to another infinitely resistive bed in which the borehole is to gauge, the configuration of the curves is very characteristic. Apparent resistivity ratios again help to identify the salt.

LIST OF SYMBOLS

	Normal Curve	*Lateral Curve*
A	current electrode	current electrode
G	bottom of armor	current ground electrode
G'	—	bottom of armor
M	measuring electrode	measuring electrode
N	measuring circuit ground electrode	measuring electrode
s	distance AM	distance from A to midpoint of MN
l	distance MN	—
Δs	—	distance MN
g	distance AG	distance AG
g'	—	distance GG'
c	bed thickness (single uniform bed)	
p	thickness of upper non-washed out zone	
q	thickness of lower non-washed out zone	
k	thickness of washed out zone	
r	drilled borehole radius	
r_k	radius of borehole in washed out zone	
R_a	apparent resistivity—resistivity recorded at any point on a curve	
R_m	mud resistivity	
x	distance of current electrode below the top of a bed or zone	

INTRODUCTION

On many older wells, where no caliper log was made, recognition of salt beds has had to depend almost entirely on information gained from the examination of drill cuttings. Since salt is usually soluble in the drilling mud, and does not appear in samples, this has not always been easy. The present study shows that in many cases salt beds may be recognized from unfocused electric logs, and that the boundaries of salt beds can be located with precision.

The resistivity of salt is almost infinite. Salt beds are almost always associated with other evaporites of very high resistivity, so this property alone cannot be used for their recognition. Salt, however, differs in that it usually gives rise to enlarged borehole diameters, attributed to solution by the mud. Changes in borehole diameter impart characteristic effects to electric log resistivity curves.

THEORY

Where rocks of low or moderate resistivity are being measured, the position of some of the electrodes in the logging system has no effect on the nature of the curves obtained. In many treatments of the subject (Schlumberger, 1950, p. 9–10; Schlumberger, 1958, p. 50–51), some of the electrodes are shown as being at the surface. Usually, in practice, all the electrodes are placed in the borehole, and where dealing with rocks of high resistivity, the position of each of them must be considered. In this study, theoretical curves have been constructed specifically for the electrode arrangement shown in Figure 1. The methods could, however, be applied to any other unfocused resistivity measuring system.

To obtain "two electrode," or "normal" curves, a constant current is passed between a current electrode A and the armor of the logging cable. The voltage between a pair of measuring electrodes M and N, located between A and the armor, is recorded. In the case of rocks of moderate or low resistivity, both N and the armor can be

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† The California Standard Co., Calgary, Alberta, Canada.

considered as being at infinite distance from A, so that they are virtually at ground potential. In this discussion they will be referred to as "ground" electrodes for measuring, and current circuits respectively. The voltage measured between M and N is thus the potential of M above ground potential. Where the surrounding medium is homogeneous, the logging current flows out from A equally in all directions, and the equipotential surfaces around A are spherical. It can then be shown (Guyod, 1944, 1952; Schlumberger, 1950) that:

$$R = 4\pi s \cdot \frac{V_{MN}}{i} \qquad (1)$$

where R is the resistivity of the medium, s is the distance between A and M (the spacing of the curve), and i is the logging current. This calibration formula is used to show the voltage measured between M and N, as apparent resistivity (R_a) on the log.

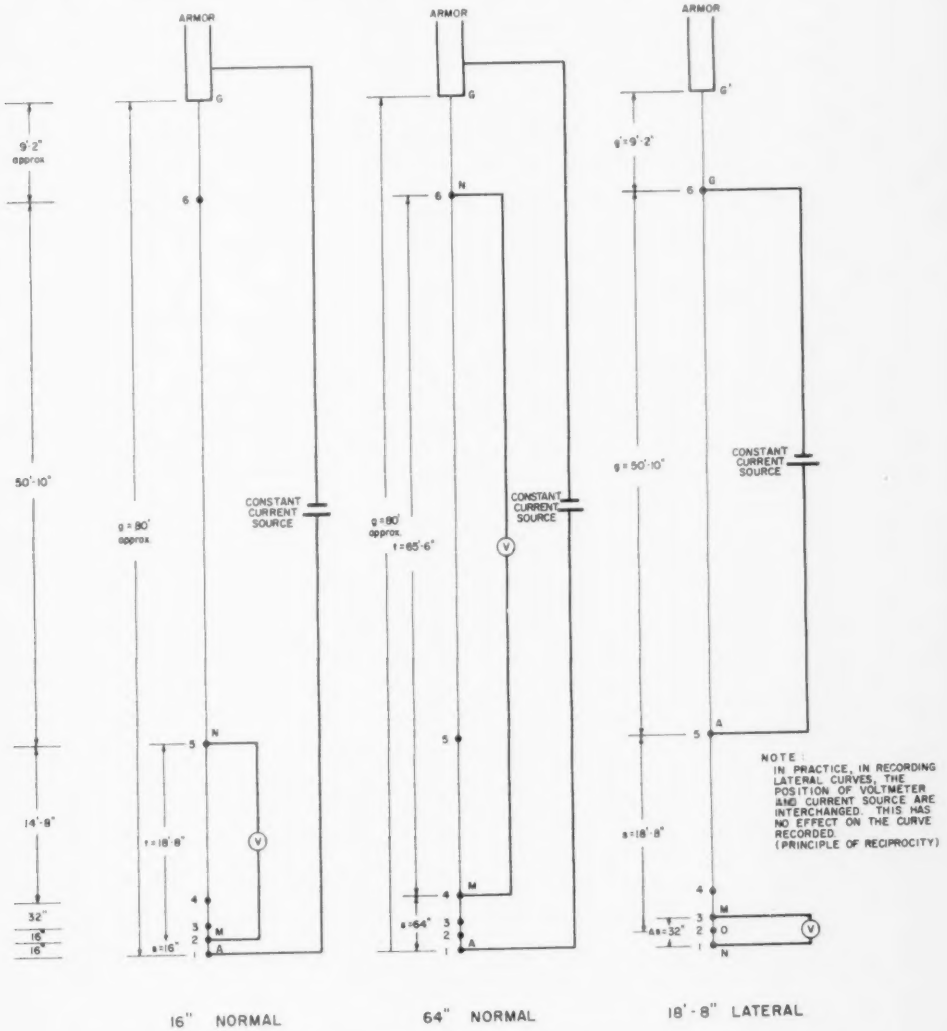

FIG. 1. Arrangement of electrodes in electric log sonde.

To record lateral curves, a constant current is maintained between a current electrode A and a current ground electrode G (the armor is not used in this case). The voltage between two closely spaced electrodes M and N is measured. Unlike the normal electrode arrangement, even in a low resistivity medium, N is not in this case at ground potential, and the curve shows the potential gradient rather than the potential. The calibration formula used for the lateral curve is:

$$R = 4\pi \frac{s^2}{\Delta s} \cdot \frac{V_{MN}}{i} \qquad (2)$$

where s is the distance from A to the mid-point between M and N, and Δs is the separation between M and N (assumed to be very small in comparison with s). In practice advantage is taken of the Principle of Reciprocity, and the roles of current and measuring electrodes are reversed. This has no effect on the nature of the curves produced (Guyod, 1944, 1952, p. 23; Schlumberger, 1950, p. 11). In this discussion it is assumed that the electrode arrangement for the lateral curve is as shown in Figure 1.

When these electrode systems are placed in a borehole, the surrounding medium is not homogeneous, and the surfaces of equal potential about A are no longer spherical. Where a system is within a bed of infinite resistivity, the current flows entirely within the borehole until leaving the confines of the bed. Some of the current travels up the hole directly from the current electrode A, to the current ground electrode (armor or G). The remainder travels down the hole to the bottom of the formation, after which it has a low resistance path back to the armor, since it is no longer confined. In the case of the lateral curve, the armor is not a current electrode, but shorts out most of what would otherwise be a relatively high resistance path down the hole to the current ground electrode G.

The mud in the borehole acts as a cylindrical conductor, the resistance of which is inversely proportional to the square of its diameter. Division of current between the path up the hole, and the path down the hole can therefore be calculated by Ohm's Law for any sonde position, in a borehole of any specified shape, however complex (see appendix). The resistance of the mud column between the two measuring electrodes can also be calculated. Using Ohm's Law again, it is possible to calculate the potential between the measuring electrodes. Finally, the apparent resistivity shown by the log is obtained from the calibration formula for the electrode arrangement used (equation 1 or 2).

In this study, general equations were derived for the apparent resistivity shown by normal and lateral electrode arrangements in a uniform borehole through a bed of infinite resistivity. Equations were also derived for a similar unit having within it a zone washed out to a greater uniform diameter. This work is presented as an appendix to this paper. The equations give apparent resistivity in terms of sonde position, mud resistivity, hole diameters, electrode spacing, and bed dimensions. They were used to construct theoretical curves for some typical situations (Figures 2, 7, 10, 11, and 13). The agreement between these theoretical curves and field logs is very close, almost every inflection of the theoretical curves being recognizable on the logs.

SALT BEDS LYING BETWEEN SHALES

In this section it will first be shown that a bed of infinite resistivity, lying between shales, can be recognized from the distinctive shape of the electric log curves, and from the ratios between the readings of the different curves. It will then be shown that when these criteria have been used to establish that a bed is infinitely resistive, any one of the curve readings can be used to calculate hole diameter. If an infinitely resistive bed can be shown to be causing enlarged hole diameter, it is immediately identified as salt.

Curve Shape

Figure 2 shows theoretical curves for 50- and 200-ft beds of infinite resistivity lying between shales. If the bed is sufficiently thin that ground electrodes for current and measuring circuits leave it before the current and measuring electrodes enter it (logging up the hole), the normal curves describe parabolas symmetrical about the mid-point of the bed. Such behavior is seen in the case of the 64-inch normal in the 50-ft bed. The 18-ft 8-inch lateral shows a linear decrease from maximum apparent resistivity at the bottom of the bed, to approximately the resistivity of the overlying shale at a point 18.7 ft from the top.

In an infinitely resistive bed is thick enough that the ground electrodes do not leave it before the current and measuring electrodes enter it, the

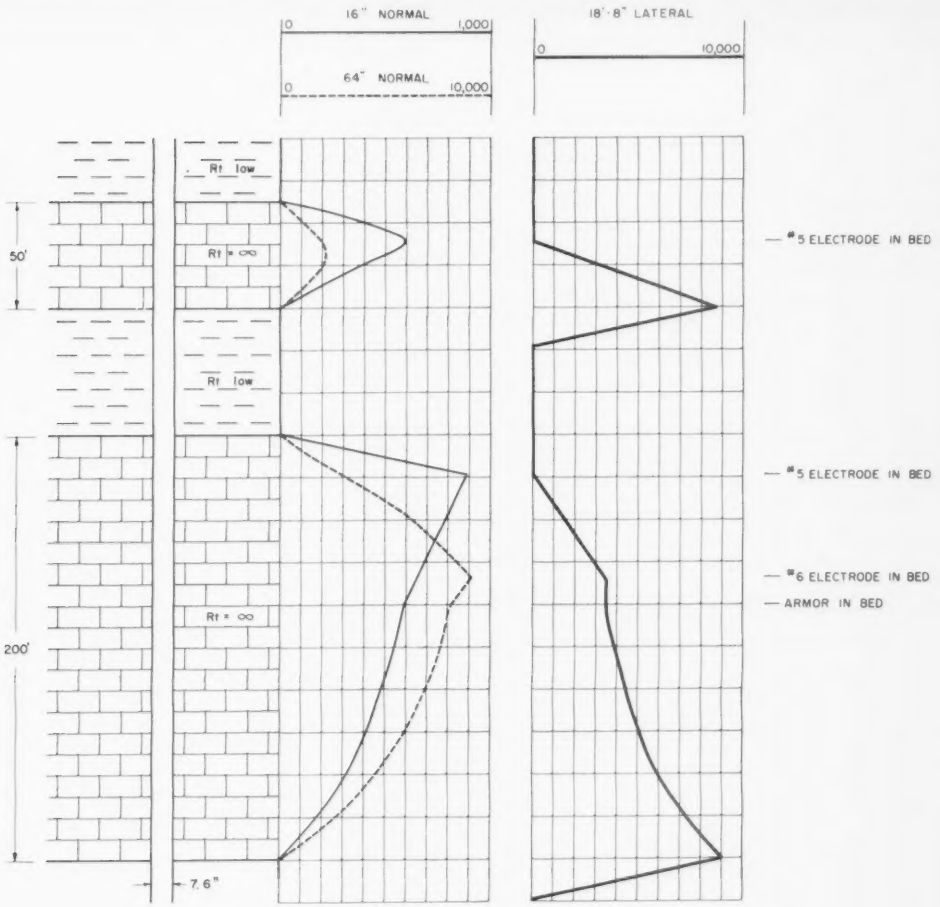

FIG. 2. Behavior of electric log resistivity curves in single infinitely resistive beds.

shape of both normals and lateral is quite distinctive. Normal curves have an asymmetric triangular shape. The 16-inch normal has its maximum reading 19.3 ft below the top of the bed, and the 64-inch normal has its maximum 68.2 ft from the top. As it does in thinner beds, the lateral curve again shows its peak reading at the lower bed boundary. The upward drop-off, however, is not linear, except for the interval between 69.5 and 18.7 ft from the top of the bed, where the current ground electrode is in the overlying shale.

Apparent Resistivity Ratios

Unless the hole diameter is known, a single curve cannot be used to determine whether a bed is of infinite resistivity. Ratios between curve readings can, however, be used. Unless formation resistivity is very high, the ground electrodes can be considered to be effectively at infinite distance from the current and measuring electrodes. The ratio in apparent resistivity can never be greater than the ratio of the spacings of the two curves, i.e. 64/16=4. (See equation 4 of the appendix.) This is substantiated by departure curves (Schlumberger, 1955, 1949) computed for measuring systems with infinitely remote ground electrodes.

In beds of high, or infinite resistivity, the ratio

between normal curve readings is usually much greater than 4. Two types of ratios may be considered:

1. Ratio between readings taken from two curves at same depth.
2. Ratio between maximum curve readings. Because of the asymmetric nature of the curves, these maximum readings will not normally be at the same depth.

Equation 7 of the appendix gives the theoretical ratio between readings of two normal curves at the same depth in an infinitely resistive bed, where all the current and measuring electrodes are within the bed:

$$\frac{R_{a1}}{R_{a2}} = \frac{s_1 t_1}{s_2 t_2}$$

where s and t represent AM and MN spacings respectively. For 16-inch and 64-inch normals, this ratio is 14.03. To ensure that all the electrodes are in the bed, readings on the curves must be taken at least 80 ft from its top. This means that the criterion can only be used in beds of considerable thickness.

It is often more convenient to use maximum apparent resistivity readings to locate infinitely resistive beds. Figure 3 shows theoretical ratios for different bed thicknesses. It will be noted that for thick beds, the ratio between 16-inch and 64-inch normals is much greater than 4, and there is little difficulty in proving beds to be infinitely resistive. For thinner beds, however, the ratio gets quite low. For such beds, the ratio between 16-inch normal and 18-ft 8-inch lateral is very useful.

Determination of Hole Diameter

The criteria of curve shape and apparent resistivity ratios allow beds of infinite resistivity to be recognized. The borehole diameter can then be found from the normal curves by reference to Figure 4, or from the lateral curve by reference to Figure 5.

As an example, Figure 6 shows a log through two typical salt beds. In both cases, curve shape is distorted by irregularities in hole diameter and possibly lithology, but comparison with Figure 2 will show that many infinite resistivity characteristics are still recognizable. Apparent resistivity maxima can be recognized on 16-inch and 64-inch normals approximately 20 and 70 ft respectively from the tops of the beds, and on the laterals at the bottoms of the beds (high resistivities between 4,500 and 4,580 ft are probably caused by slightly decreased hole diameter). Ratios between these maxima are in accordance with theoretical ratios for beds of infinite resistivity shown in Figure 3. The foregoing evidence indicates the beds to be infinitely resistive. The apparent resistivity maxima for the three curves can now be used again to determine hole diameter by use of Figures 4 and 5. Hole diameters calculated from each of the three curves agree within an inch for both beds. The diameters are 18 and 22 inches for upper and lower beds respectively. Since the drilled diameter of the hole was only 9 inches, the beds are clearly washed out. The combination of infinite resistivity and increased hole diameter indicates the beds to be salt.

SALT ADJACENT TO BEDS OF INFINITE RESISTIVITY

Salt usually occurs in evaporite sequences with dense dolomites or anhydrites. The beds above or below it are frequently highly resistive. Where salt is washed out, the situation can be recognized from the characteristic configuration of the electric log resistivity curves. Figure 7 shows theoretical resistivity curves for a 100-ft salt bed lying between 200-ft beds of infinite resistivity. The salt is assumed to be washed out to 3.16 times the drilled diameter. Figures 8 and 9 are comparisons of field logs with theoretical curves. The close agreement between the two confirms the soundness of the theory used to compute the theoretical curves. Figures 10 and 11 are theoretical resistivity curves for situations in which one of the surrounding beds is shale and the other is infinitely resistive.

In general, salt beds in infinitely resistive sequences appear on all resistivity curves as zones of lower apparent resistivity. Figure 12 shows how the curve configurations near the interface between a salt bed and another bed of infinite resistivity serve to distinguish the salt from a shaly zone. Considering first the case where the salt or shaly bed lies below the other infinitely resistive bed, it will be noted that a lateral curve maximum coincides exactly with the interface in either case. The lateral curve is therefore useful in establishing the position of the interface. The salt can then be distinguished from the shaly zone by the changes in apparent resistivity shown by the normal curves below the interface. The 16-inch normal decreases rapidly over 19.3 ft, while the

(*Continued on page 337*)

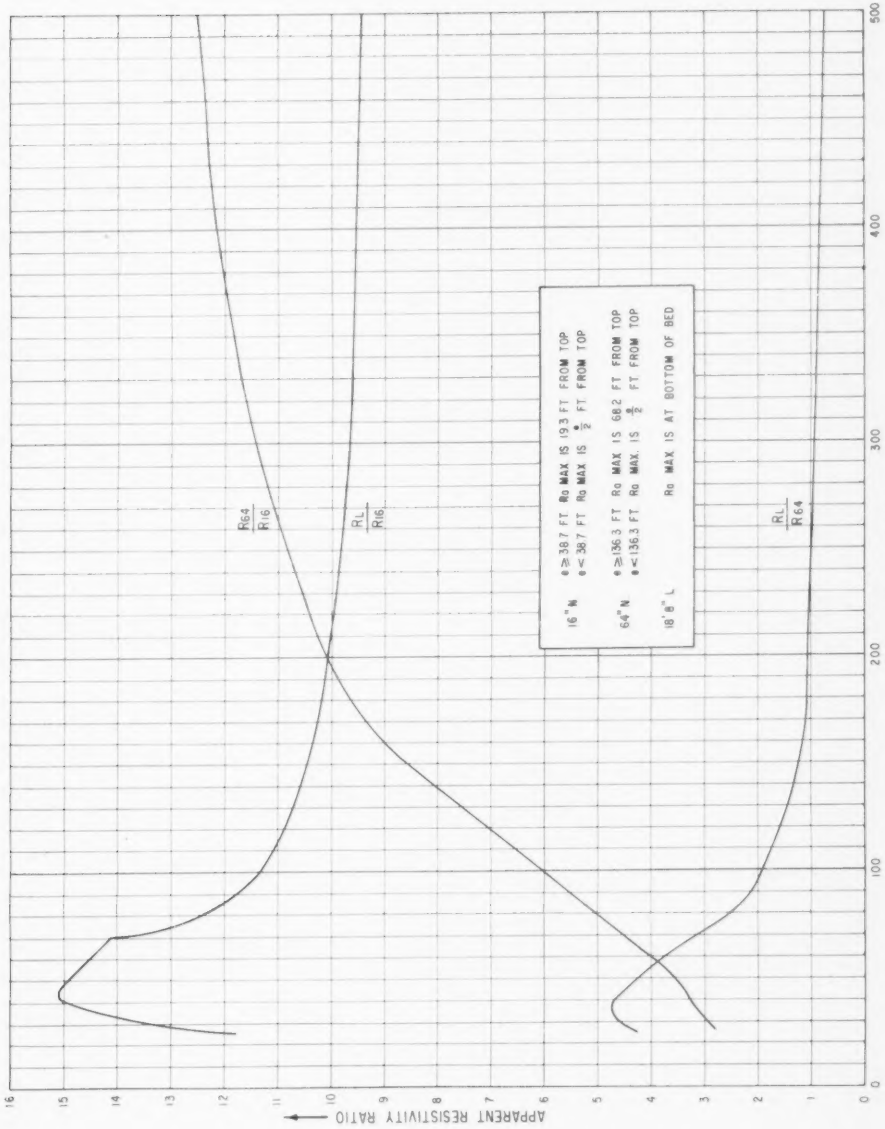
APPARENT RESISTIVITY RATIO
BED THICKNESS e
R64/R16
RL/R16
RL/R64
16" N
e ≥ 38.7 FT Ro MAX IS 19.3 FT FROM TOP
e < 38.7 FT Ro MAX IS e/2 FT FROM TOP
64" N
e ≥ 136.3 FT Ro MAX IS 68.2 FT FROM TOP
e < 136.3 FT Ro MAX IS e/2 FT FROM TOP
18' 8" L
Ro MAX IS AT BOTTOM OF BED

FIG. 3. Ratios of apparent resistivity maxima for beds of infinite resistivity.

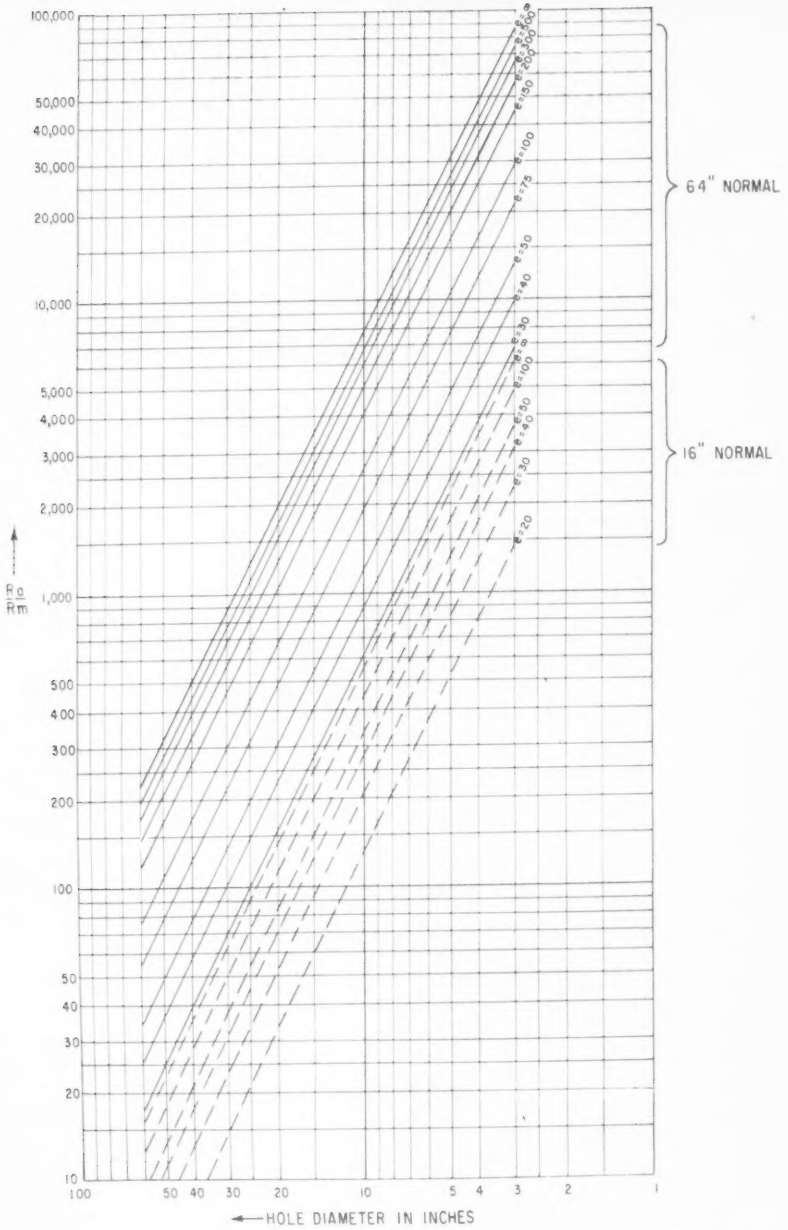

FIG. 4. Determination of hole diameter from 16″ or 64″ normal cuves for beds of infinite resistivity.

16:N $\begin{cases} e \geq 38.7 \text{ ft. read } R_a \text{ at } 19.3 \text{ ft from top of bed} \\ e < 38.7 \text{ ft read } R_a \text{ at middle of bed} \end{cases}$

64:N $\begin{cases} e \geq 136.3 \text{ ft read } R_a \text{ at } 68.2 \text{ ft from top of bed} \\ e < 136.3 \text{ ft read } R_a \text{ at middle of bed} \end{cases}$

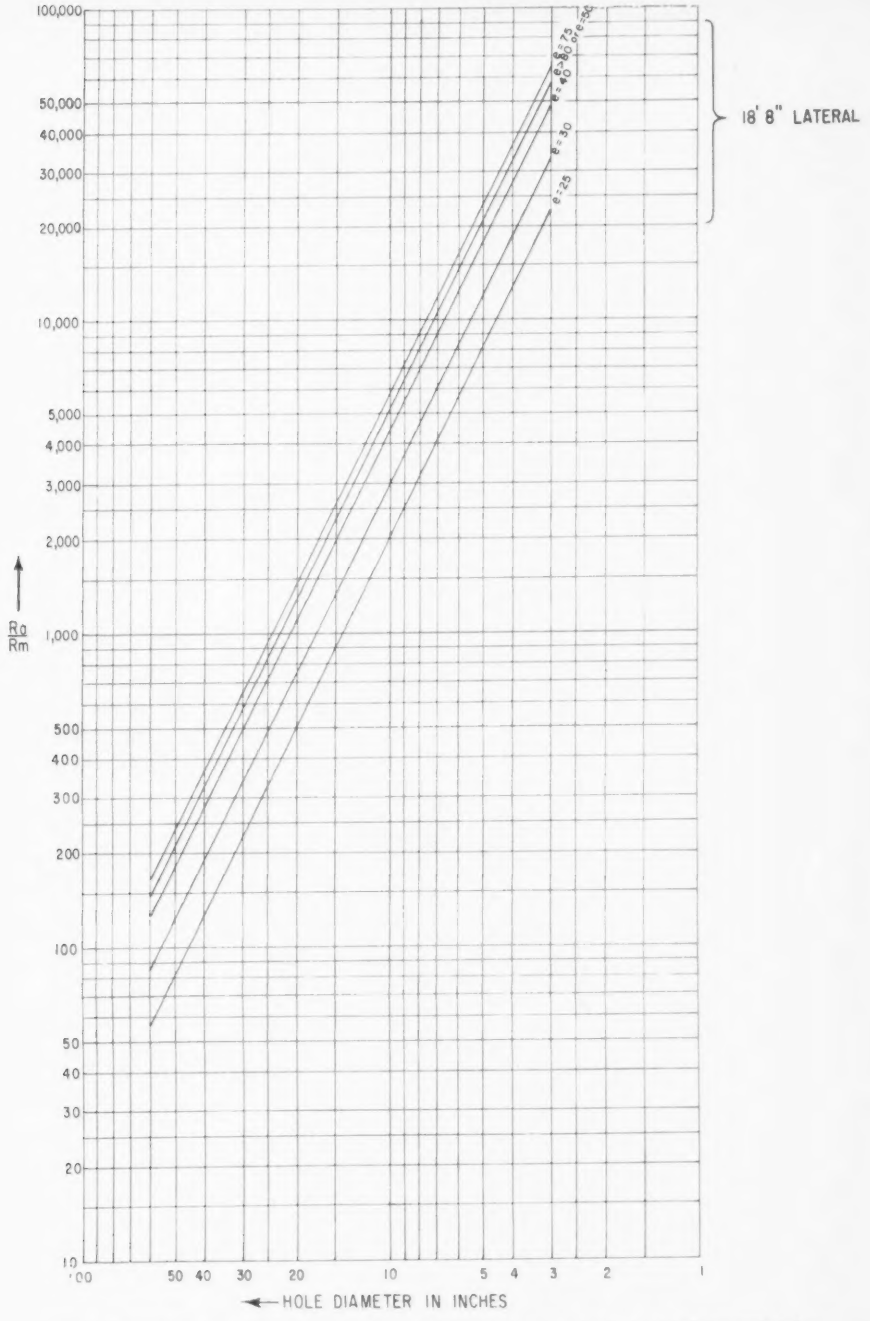

FIG. 5. Determination of hole diameter from 18′8″ lateral curves for beds of infinite resistivity. Read R_0 at bottom of bed

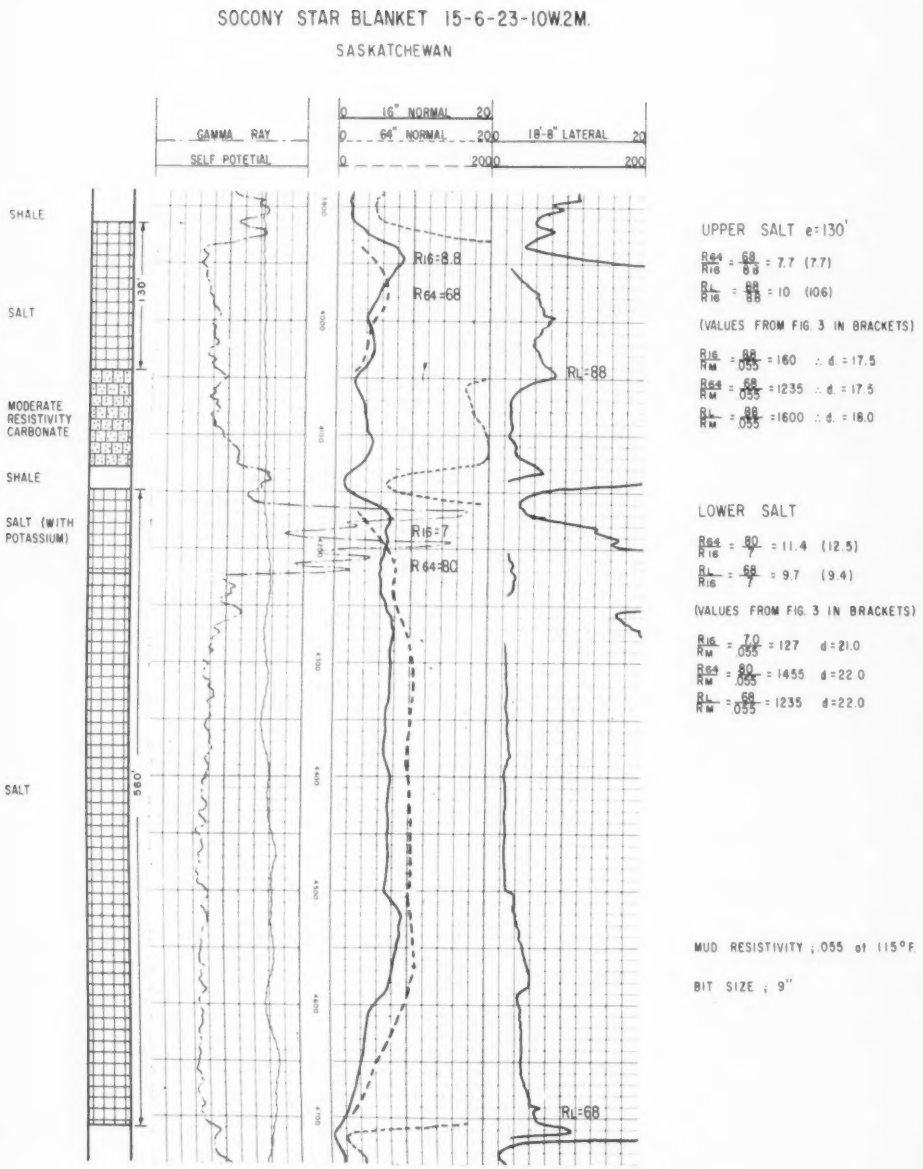

FIG. 6. Identification of salt lying between relatively low resistivity beds.

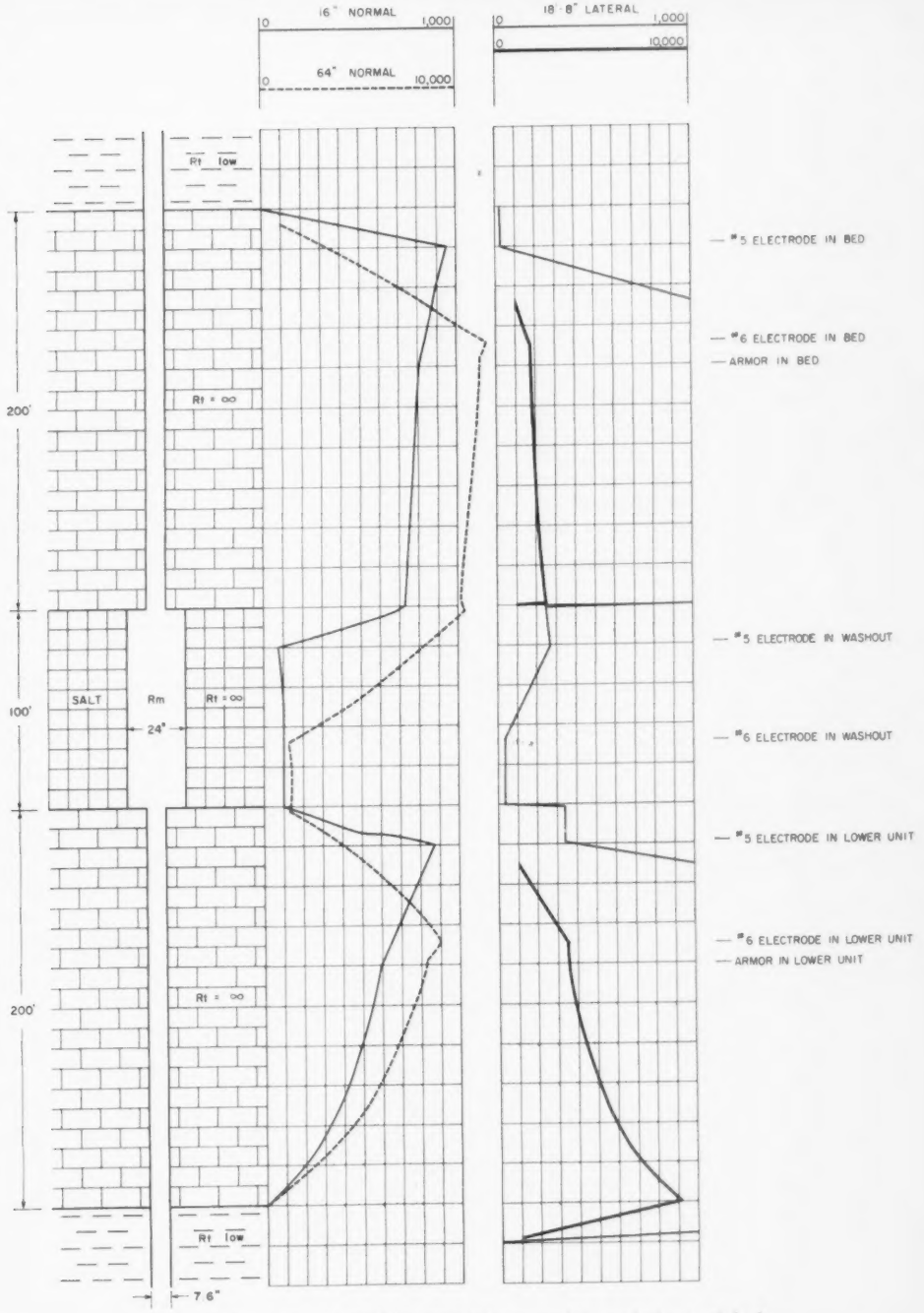

FIG. 7. Behavior of electric log resistivity curves in a washed out salt bed surrounded by other beds of infinite resisitivity.

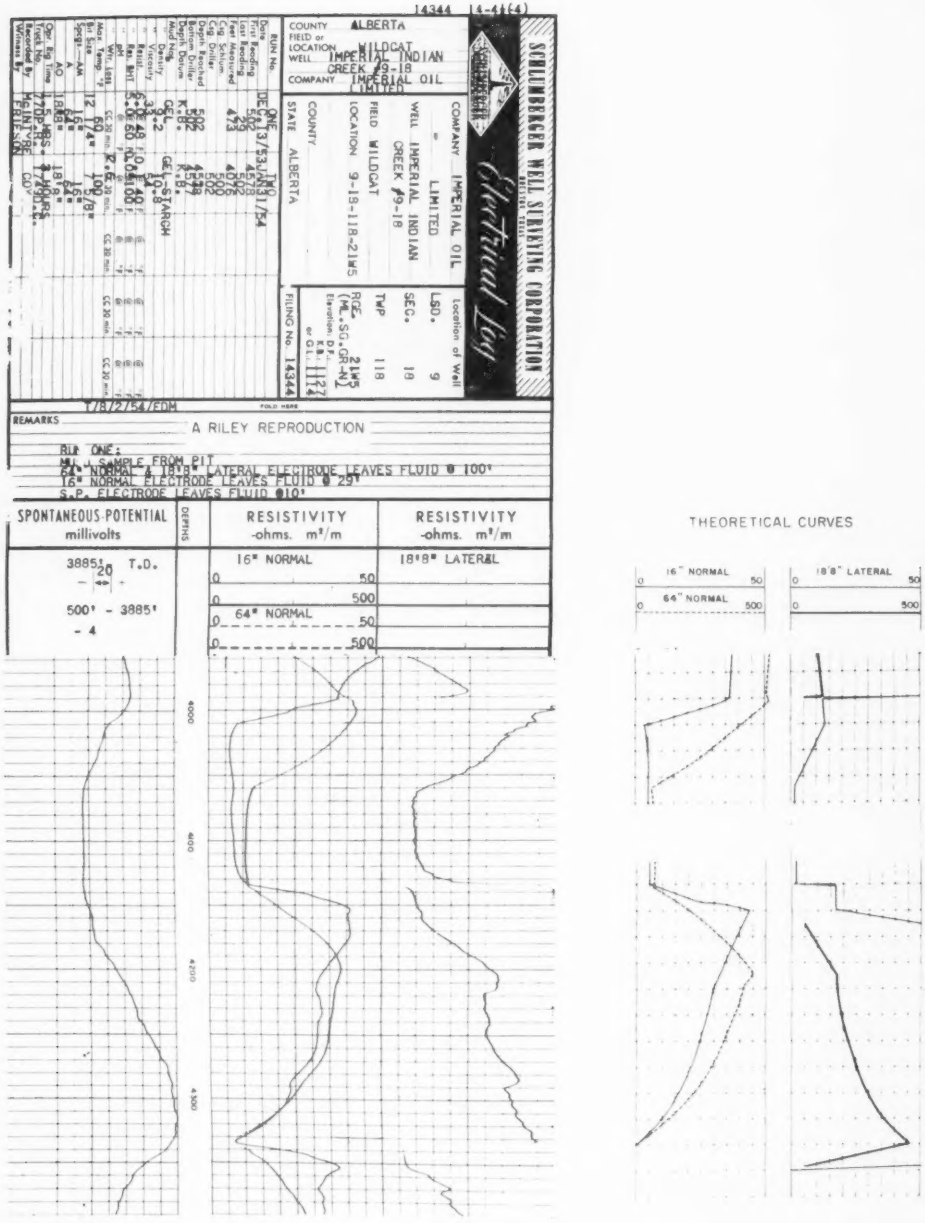

FIG. 8. Comparison of theoretical electric log curves through a salt bed with an actual log.

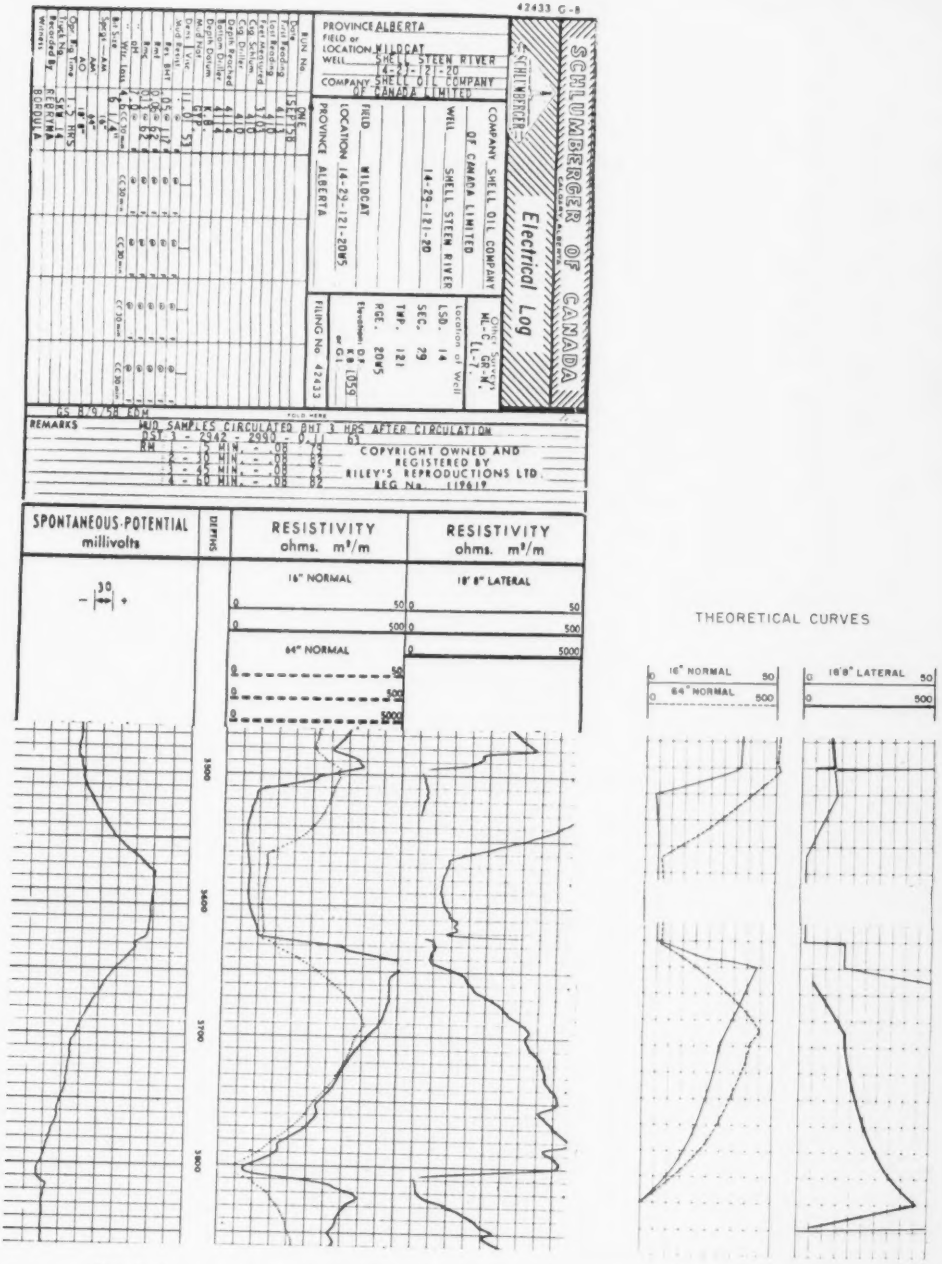

FIG. 9. Comparison of theoretical electric log curves through a salt bed with an actual log.

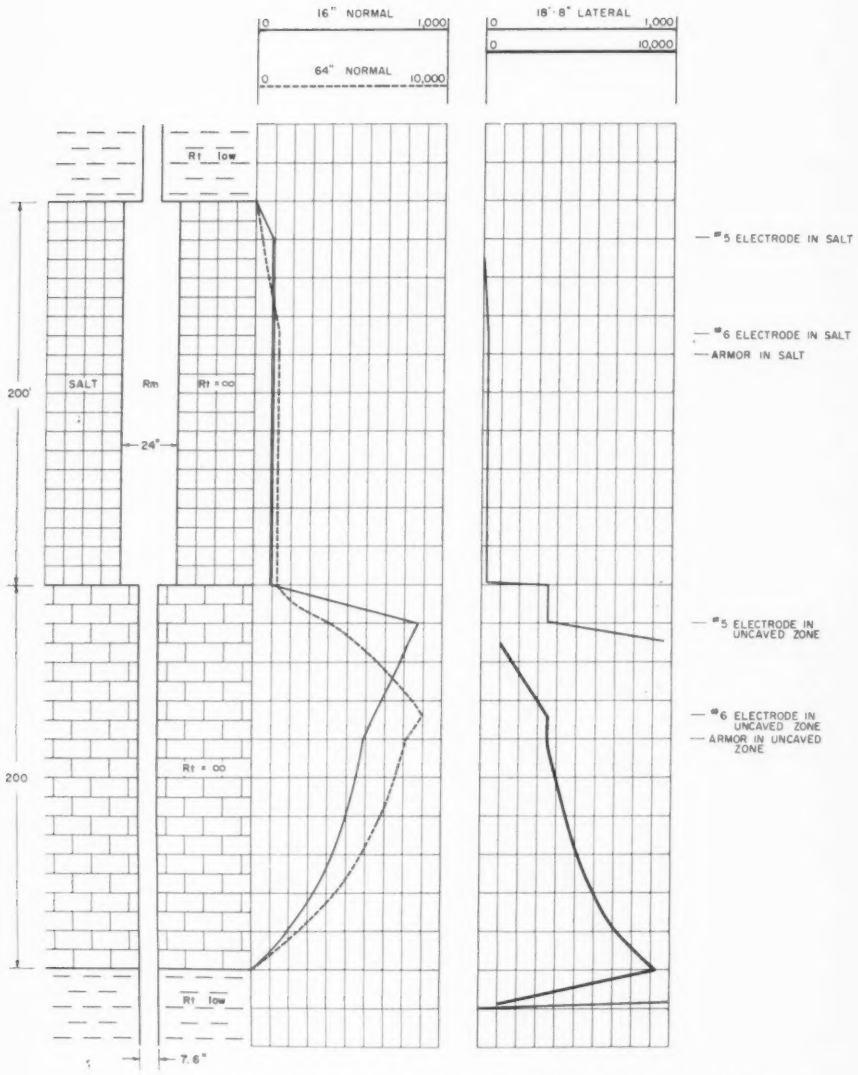

FIG. 10. Behavior of electric log resistivity curves in a washed out salt bed overlain by shale and underlain by another bed of infinite resistivity.

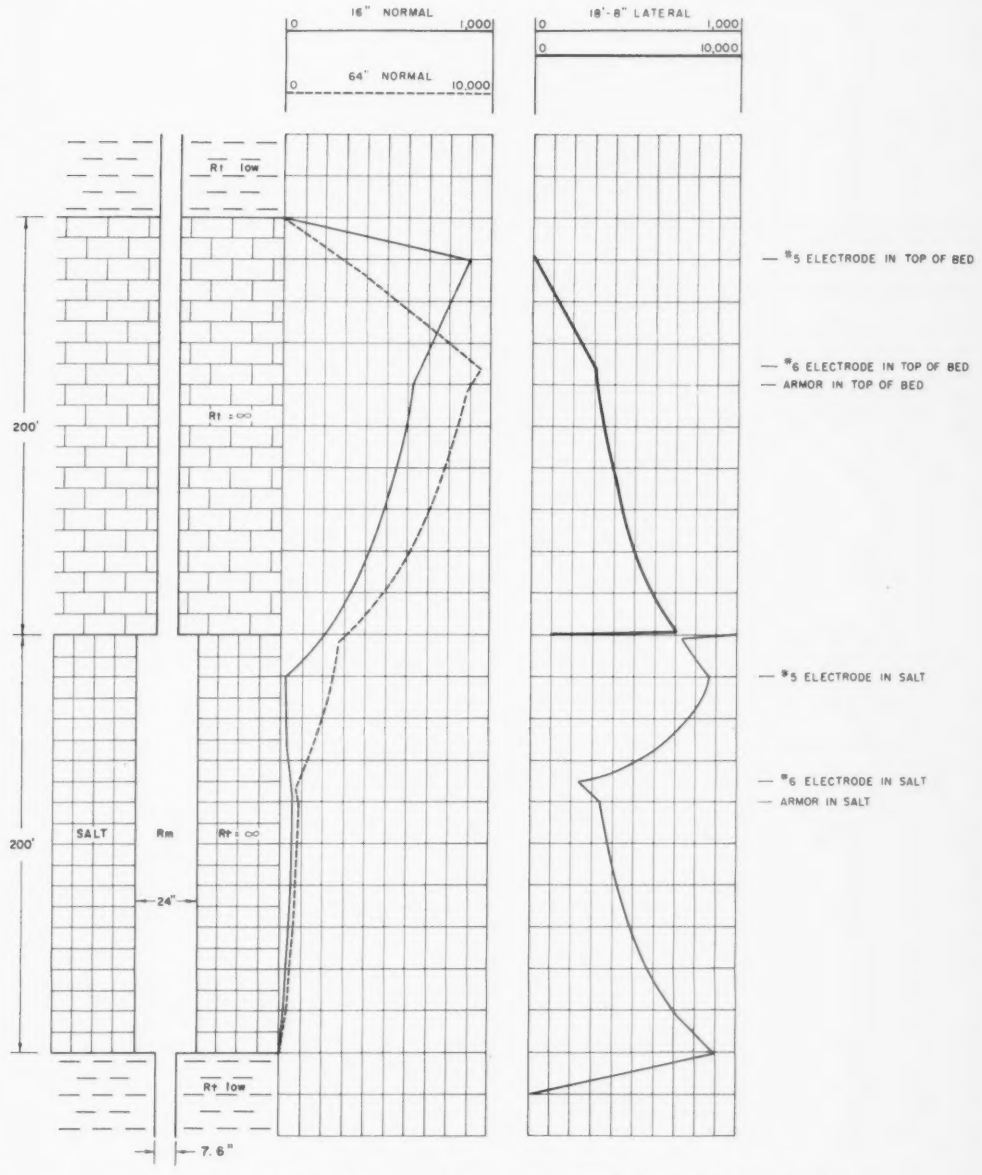

FIG. 11. Behavior of electric log resistivity curves in a washed out salt bed overlain by another bed of infinite resistivity and underlain by shale.

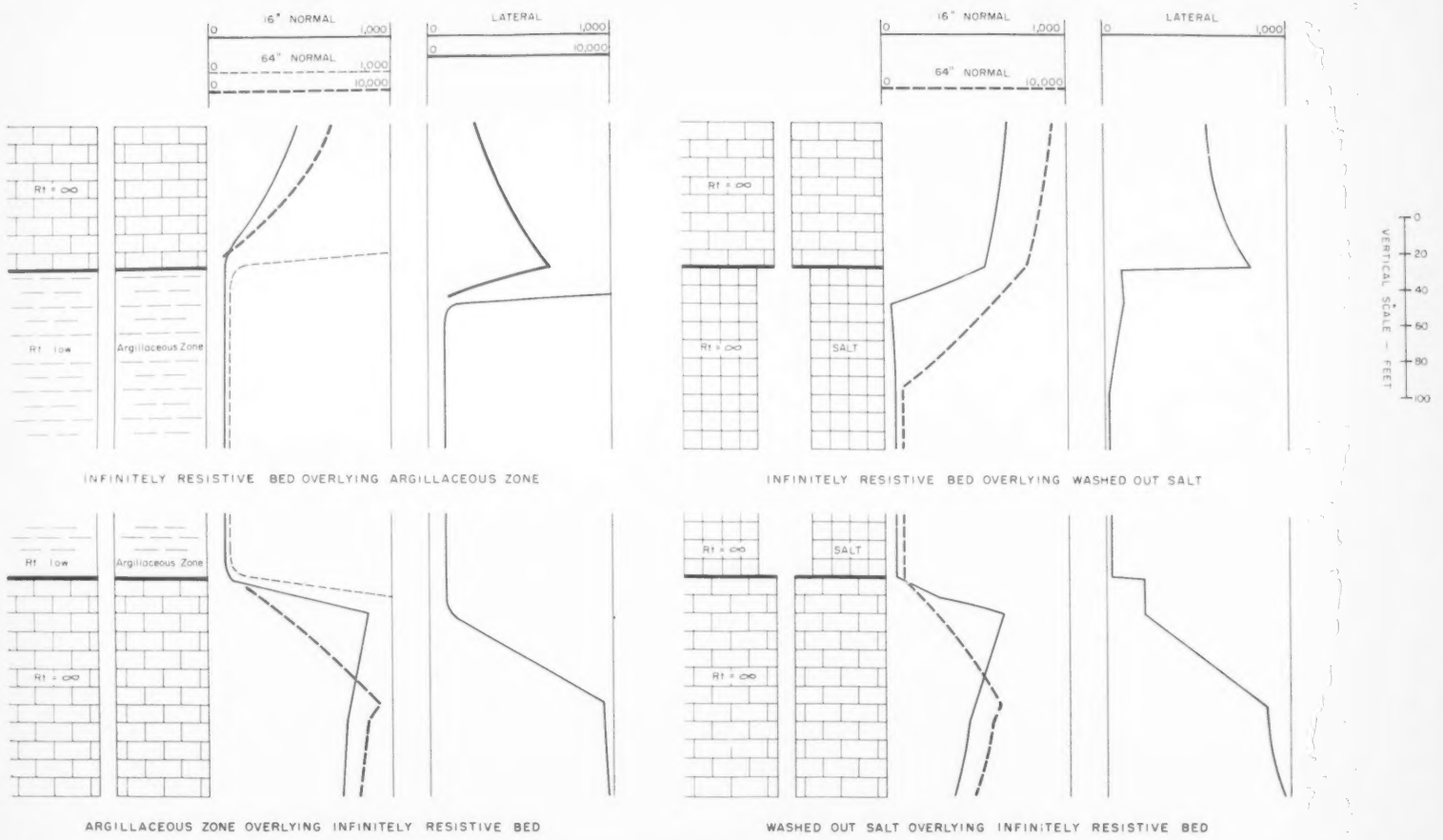

FIG. 12. Comparison of electric log resistivity curves at boundaries of argillaceous zones and washed out salt beds.

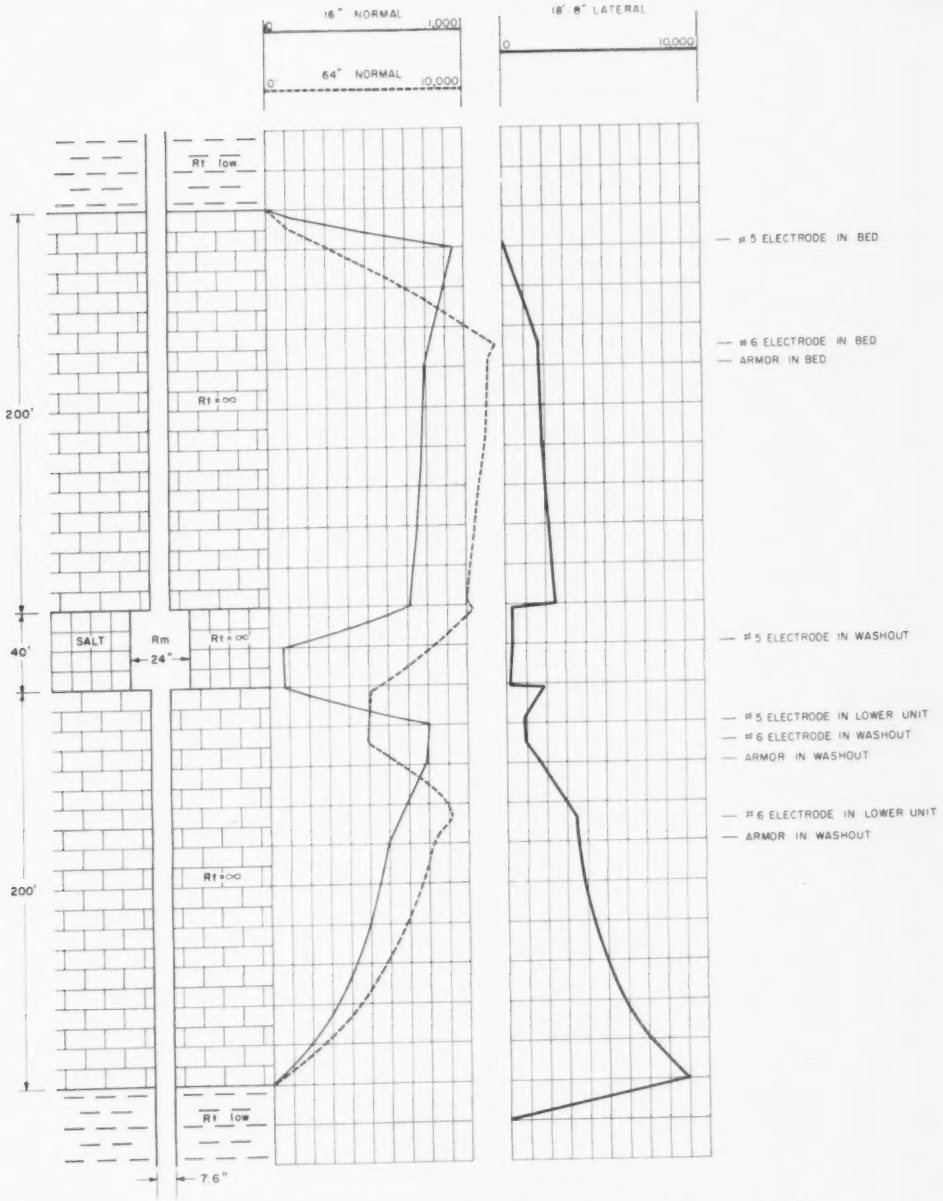

FIG. 13. Behavior of electric log resistivity curves in a thin washed out salt bed surrounded by other beds of infinite resistivity.

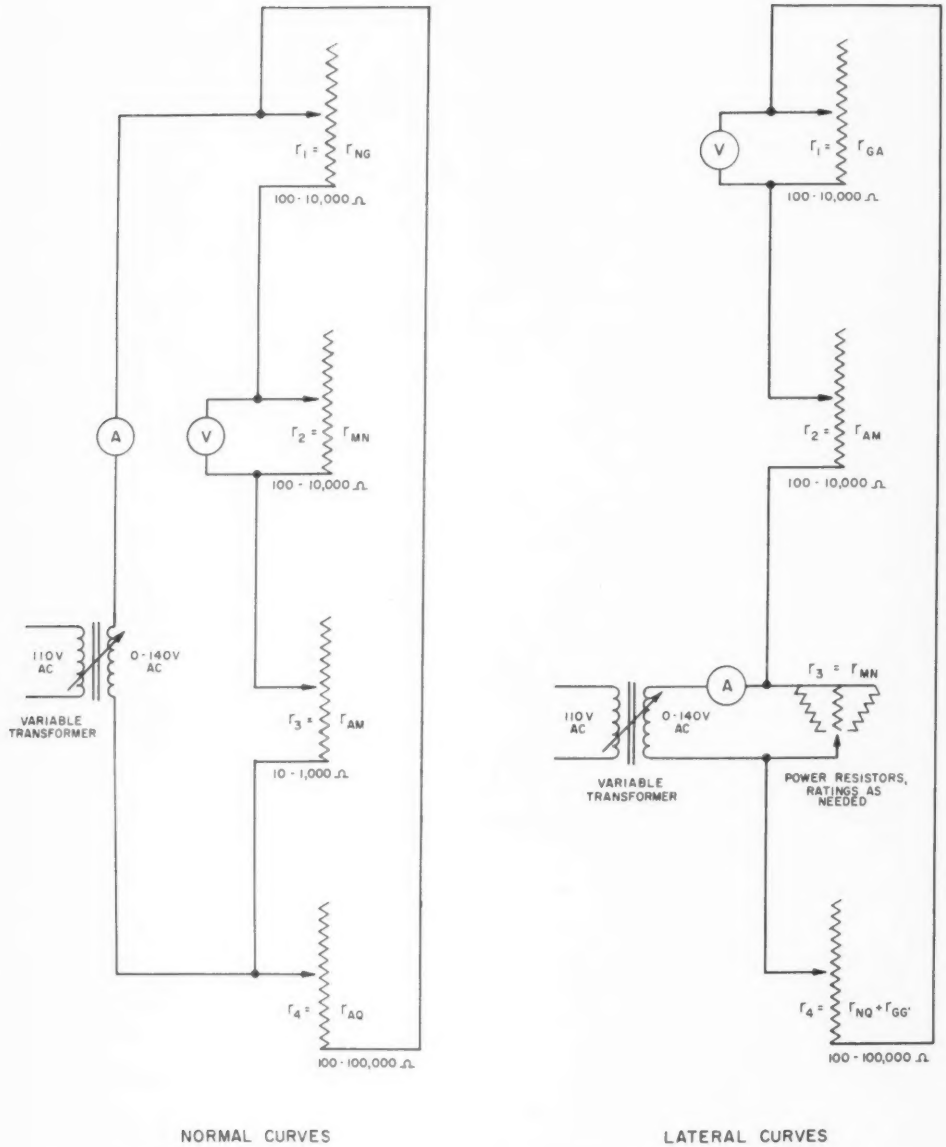

FIG. 14. Analogue circuits for obtaining synthetic electric log resistivity curves for beds of infinite resistivity.

64-inch normal decreases over 68.2 ft.

Considering next the case where the salt or shaly bed overlies the other infinitely resistive bed, it will be seen that the behavior of the normal curves is similar in either case, and can be used to locate the position of the boundary. The characteristic step in the lateral curve immediately below the salt then distinguishes it from the shaly zone.

The ratios of the three curve readings are also useful in identifying salt adjacent to infinitely resistive beds. The ratio of readings of 64-inch normal to 16-inch normal can be up to 14, below a point 70 ft from the top of the bed. In the top 70 ft, the ratio is even higher. In an argillaceous zone the ratio should never exceed 4.

The changes in apparent resistivity shown by the lateral curve at the top and the bottom of a washed out zone are in the same ratio as the change in cross-sectional area of the borehole. The diameter of the washed out hole can thus be quickly found. In computing the curves shown in Figure 7, it was assumed that the borehole was washed out to 3.16 times its drilled diameter, or 10 times its drilled cross-sectional area. It will be noted that the change in apparent resistivity at the top and bottom of the zone is exactly 10.

Thin Salt Beds in Infinitely Resistive Sequences

Many evaporite sequences contain salt beds thinner than those considered so far. Where bed thicknesses are less than 80 ft, effects caused by the top of the bed overlap with those at the bottom. The resulting curve shapes can be very complicated, especially if a number of salt stringers are involved. Figure 13 shows curve behavior for a single salt bed 40 ft thick, lying between other infinitely resistive rocks. There is no theoretical difficulty in computing curve shape for any combination of beds of different thicknesses. However, the number of possibilities is very great, and calculation would be tedious. This work can be facilitated by using an analogue circuit consisting of four variable resistors or cascade resistance boxes, each representing the resistance of the mud column between one pair of electrodes. Figure 14 is a schematic diagram of the analogue circuit.

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Schlumberger Well Survey Corporation, 1949, Resistivity departure curves, beds of finite thickness, document 3.

——— 1950, Interpretation hand-book for resistivity logs, document 4.

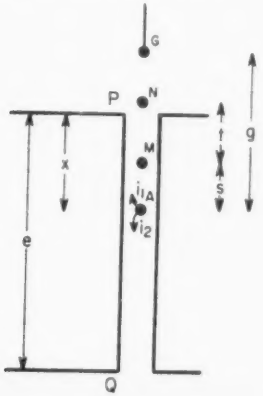
——— 1955, Resistivity departure curves, beds of infinite thickness, document 7.

———, 1958, Introduction to Schlumberger well logging, document 8.

APPENDIX 1

BEHAVIOR OF A NORMAL DEVICE IN A SINGLE BED OF INFINITE RESISTIVITY LYING BETWEEN SHALES

Case 1. *Return Electrode for Measuring Circuit Outside Bed $s<x<(s+t)$*



Difference in potential between A and P (Ohm's Law)

$$V_{AP} = R_m \frac{x}{\pi r^2} i_1.$$

Difference in potential between A and Q (Ohm's Law)

$$V_{AQ} = R_m \frac{(e-x)}{\pi r^2} (i - i_1).$$

If resistivity of surrounding beds is low, potential at P and Q is almost zero.

$$V_{AP} = V_{AQ}$$

$$\therefore \; i_1 = \frac{(e-x)}{e} i.$$

Also

$$V_{MN} = V_{MP} = R_m \frac{(x - s)}{\pi r^2} i_1 \quad \text{(Ohm's Law)}.$$

The calibration formula for a normal sonde is:

$$R_a = 4\pi s \frac{V_{MN}}{i}$$

$\therefore$ apparent resistivity shown by the log is:

$$(1) \qquad R_a = 4sR_m \left(\frac{x - s}{r^2}\right)\left(\frac{e - x}{e}\right).$$

Maximum Value of R_a

The maximum value of R_a is when

$$x = \frac{e + s}{2}$$

i.e. when

$$(2) \qquad R_a = \frac{sR_m}{er^2}(e - s)^2.$$

If s is small compared to e, maximum resistivity is:

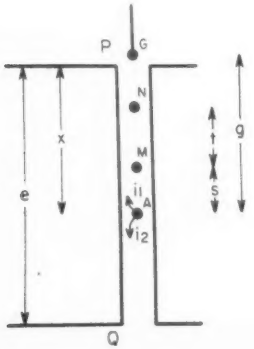
$$(3) \qquad R_a = \frac{esR_m}{r^2}.$$

Ratio of Apparent Resistivities for Curves of Different Spacing

Assuming s small compared to e, ratio of apparent resistivity maxima is:

$$(4) \qquad \frac{R_{a1}}{R_{a2}} = \frac{s_1}{s_2}.$$

Case 2. *Return Electrode for Measuring Circuit Inside Bed, Return Electrode for Current Circuit Outside Bed $(s+t) < x < g$*

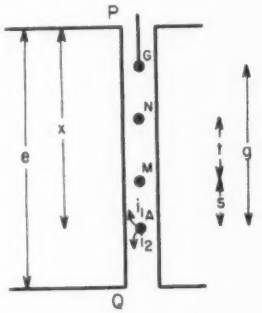


Division of current unchanged from case 1. But

$$V_{MN} = R_m \frac{l}{\pi r^2} i_1$$

$$R_a = 4sR_m \frac{l}{r^2}\left(\frac{e - x}{e}\right). \qquad (5)$$

Case 3. *All Electrodes Inside Bed $g < x < e$*



Difference in potential between A and G (Ohm's Law)

$$V_{AG} = R_m \frac{g}{\pi r^2} i_1.$$

Difference in potential between A and Q (Ohm's Law)

$$V_{AQ} = R_m \frac{(e - x)}{\pi r^2}(i - i_1).$$

If resistivity of surrounding beds is low, almost all potential drop along path $AQPG$ is in the section AQ. Therefore potential at Q is almost zero.

$$V_{AQ} = V_{AG}$$

$$i_1 = \left(\frac{e - x}{g + e - x}\right) i$$

$$V_{MN} = R_m \frac{l}{\pi r^2} i_1 \quad \text{(Ohm's Law)}$$

apparent resistivity shown for a normal sonde is:

$$R_a = 4sR_m \frac{l}{r^2}\left(\frac{e - x}{g + e - x}\right). \qquad (6)$$

Ratio of Apparent Resistivities for Curves of Different Spacing

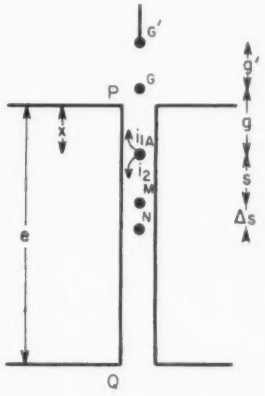
Using equation 6:

$$\frac{R_{a1}}{R_{a2}} = \frac{s_1 l_1}{s_2 l_2}. \qquad (7)$$

APPENDIX 2

BEHAVIOR OF A LATERAL DEVICE IN A SINGLE BED OF INFINITE RESISTIVITY LYING BETWEEN SHALES

Case 1. *Current Return Electrode Outside Bed.* $0<x<g$



Difference in potential between A and P (Ohm's Law)

$$V_{AP} = R_m \frac{x}{\pi r^2}(i - i_2).$$

Difference in potential between A and Q (Ohm's Law)

$$V_{AQ} = R_m \frac{(e - x)}{\pi r^2} i_2.$$

If resistivity of surrounding beds is low, potential at P and Q is almost zero.

$$V_{AP} = V_{AQ}$$

$$\therefore \; i_2 = \frac{x}{e} i.$$

Also

$$V_{MN} = R_m \frac{\Delta s}{\pi r^2} i_2 \quad \text{(Ohm's Law)}.$$

The calibration formula for a lateral device is:

$$R_a = 4\pi \frac{s^2}{\Delta s} \cdot \frac{\Delta V}{i}.$$

$\therefore$ apparent resistivity shown by the log is:

$$R_a = 4 \frac{s^2}{r^2} R_m \left(\frac{x}{e}\right). \tag{8}$$

Maximum value of R_a

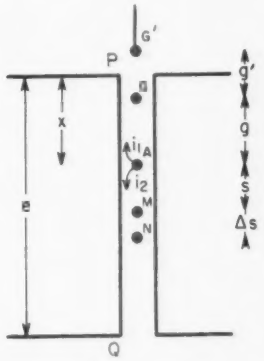
The above equation represents a straight line. Apparent resistivity increases from zero when $x=0$ to a maximum value at the bottom of the bed where:

$$R_a = 4s^2 R_m \frac{(e - s)}{er^2}. \tag{9}$$

As

$$e \to \infty \quad R_a \to 4R_m \left(\frac{s}{r}\right)^2. \tag{10}$$

Case 2. *Current Return Electrode Inside Bed. Armor Outside Bed* $g<x<(g+g)$



Difference in potential between A and G (Ohm's Law)

$$V_{AG} = R_m \frac{g}{\pi r^2}(i - i_2).$$

Total potential difference along path AQ and PG

$$V_{AQPG} = R_m \frac{(e - g)}{\pi r^2} i_2.$$

But

$$V_{AG} = V_{AQPG}$$

$$\therefore \; i_2 = \frac{g}{e} i$$

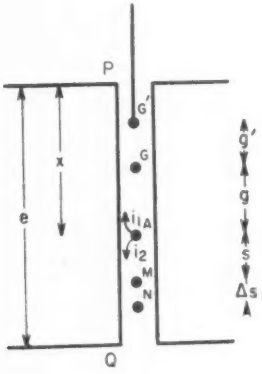
$$V_{MN} = R_m \frac{\Delta s}{\pi r^2} i_2$$

$\therefore$ apparent resistivity shown by the log is.

$$R_a = 4 \frac{s^2}{r^2} R_m \left(\frac{g}{e} \right). \tag{11}$$

Case 3. *All Electrodes Inside Bed.*

$$(g + g') < x < (e - s)$$



Difference in potential between A and G (Ohm's Law)

$$V_{AG} = R_m \frac{g}{\pi r^2} (i - i_2).$$

Total potential difference along path AQ and PG.

$$V_{AQPG} = R_m \frac{(e - x + g')}{\pi r^2} i_2$$

(note that PG' is shorted out by the armor).

But

$$V_{AG} = V_{AQPG}$$

$$\therefore \; i_2 = \left(\frac{g}{e - x + g + g'} \right) i.$$

Also

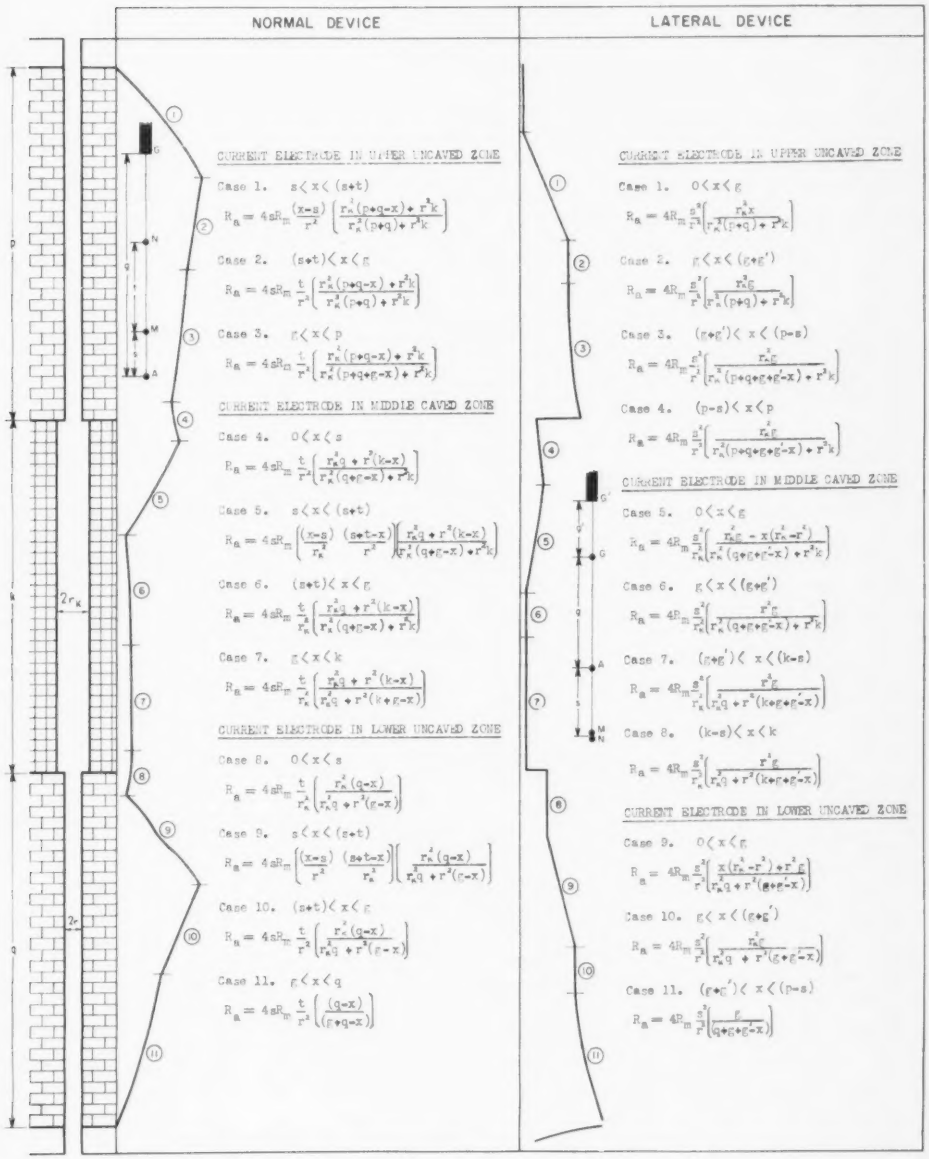
$$V_{MN} = R_m \frac{\Delta s}{\pi r^2} i_2.$$

$\therefore$ apparent resistivity shown by the log is:

$$R_a = 4 \frac{s^2}{r^2} R_m \left(\frac{g}{e - x + g + g'} \right). \tag{12}$$

APPENDIX 3

BEHAVIOR OF NORMAL AND LATERAL DEVICES IN A UNIT OF INFINITE RESISTIVITY CONTAINING WITHIN IT A WASHED OUT OR CAVED ZONE


NORMAL DEVICE
LATERAL DEVICE
CURRENT ELECTRODE IN UPPER UNCAVED ZONE
Case 1. s < x < (s+t)
$R_a = 4sR_m \frac{(x-s)}{r^2}\left(\frac{r_k^2(p+q-x)+r^2k}{r_k^2(p+q)+r^2k}\right)$
Case 2. (s+t) < x < p
$R_a = 4sR_m \frac{t}{r^2}\left(\frac{r_k^2(p+q-x)+r^2k}{r_k^2(p+q)+r^2k}\right)$
Case 3. p < x < p
$R_a = 4sR_m \frac{t}{r^2}\left(\frac{r_k^2(p+q-x)+r^2k}{r_k^2(p+q+g-x)+r^2k}\right)$
CURRENT ELECTRODE IN MIDDLE CAVED ZONE
Case 4. 0 < x < s
$R_a = 4sR_m \frac{t}{r^2}\left(\frac{r_k^2q+r^2(k-x)}{r_k^2(q+g-x)+r^2k}\right)$
Case 5. s < x < (s+t)
$R_a = 4sR_m \left(\frac{(x-s)}{r_k^2}\frac{(s+t-x)}{r^2}\right)\left(\frac{r_k^2q+r^2(k-x)}{r_k^2(q+g-x)+r^2k}\right)$
Case 6. (s+t) < x < p
$R_a = 4sR_m \frac{t}{r_k^2}\left(\frac{r_k^2q+r^2(k-x)}{r_k^2(q+g-x)+r^2k}\right)$
Case 7. p < x < k
$R_a = 4sR_m \frac{t}{r_k^2}\left(\frac{r_k^2q+r^2(k-x)}{r_k^2q+r^2(k+g-x)}\right)$
CURRENT ELECTRODE IN LOWER UNCAVED ZONE
Case 8. 0 < x < s
$R_a = 4sR_m \frac{t}{r_k^2}\left(\frac{r_k^2(q-x)}{r_k^2q+r^2(g-x)}\right)$
Case 9. s < x < (s+t)
$R_a = 4sR_m \left(\frac{(x-s)}{r^2}\frac{(s+t-x)}{r_k^2}\right)\left(\frac{r_k^2(q-x)}{r_k^2q+r^2(g-x)}\right)$
Case 10. (s+t) < x < p
$R_a = 4sR_m \frac{t}{r^2}\left(\frac{r_k^2(q-x)}{r_k^2q+r^2(g-x)}\right)$
Case 11. p < x < q
$R_a = 4sR_m \frac{t}{r^2}\left(\frac{(q-x)}{(g+q-x)}\right)$
CURRENT ELECTRODE IN UPPER UNCAVED ZONE
Case 1. 0 < x < p
$R_a = 4R_m \frac{s^2}{r^2}\left(\frac{r_k^2x}{r_k^2(p+q)+r^2k}\right)$
Case 2. p < x < (p+g')
$R_a = 4R_m \frac{s^2}{r^2}\left(\frac{r_k^2p}{r_k^2(p+q)+r^2k}\right)$
Case 3. (p+g') < x < (p-s)
$R_a = 4R_m \frac{s^2}{r^2}\left(\frac{r_k^2p}{r_k^2(p+q+g+g'-x)+r^2k}\right)$
Case 4. (p-s) < x < p
$R_a = 4R_m \frac{s^2}{r^2}\left(\frac{r_k^2p}{r_k^2(p+q+g+g'-x)+r^2k}\right)$
CURRENT ELECTRODE IN MIDDLE CAVED ZONE
Case 5. 0 < x < p
$R_a = 4R_m \frac{s^2}{r_k^2}\left(\frac{r_k^2p-x(r_k^2-r^2)}{r_k^2(q+g+g'-x)+r^2k}\right)$
Case 6. p < x < (p+g')
$R_a = 4R_m \frac{s^2}{r_k^2}\left(\frac{r^2p}{r_k^2(q+g+g'-x)+r^2k}\right)$
Case 7. (p+g') < x < (k-s)
$R_a = 4R_m \frac{s^2}{r_k^2}\left(\frac{r^2p}{r_k^2q+r^2(k+g+g'-x)}\right)$
Case 8. (k-s) < x < k
$R_a = 4R_m \frac{s^2}{r_k^2}\left(\frac{r^2p}{r_k^2q+r^2(k+g+g'-x)}\right)$
CURRENT ELECTRODE IN LOWER UNCAVED ZONE
Case 9. 0 < x < p
$R_a = 4R_m \frac{s^2}{r^2}\left(\frac{x(r_k^2-r^2)+r^2p}{r_k^2q+r^2(g+g'-x)}\right)$
Case 10. p < x < (p+g')
$R_a = 4R_m \frac{s^2}{r^2}\left(\frac{r_k^2p}{r_k^2q+r^2(g+g'-x)}\right)$
Case 11. (p+g') < x < (p-s)
$R_a = 4R_m \frac{s^2}{r^2}\left(\frac{r}{(q+g+g'-x)}\right)$

GEOPHYSICS, VOL. XXVI, NO. 3 (JUNE, 1961), PP. 342–354, 9 FIGS.

THEORETICAL HORIZONTAL RESISTIVITY PROFILES OVER HEMISPHERICAL SINKS*

KENNETH L. COOK† AND RUSSELL L. GRAY‡

Abstract: An album of 40 sets (about 200 different curves)[1] of theoretical horizontal resistivity profiles over and near outcropping hemispherical sinks shows the effects of sink diameter, reflection factor k, and distance of the traverse from the center of the sink upon the magnitude and shape of the apparent resistivity curves. Curves for sink diameters of $16a$, $8a$, $6a$, $4a$, $2a$, a, and $0.5a$, and reflection factors k of ± 0.8, ± 0.6, ± 0.4, and ± 0.2 are included. The values of apparent resistivity for both the Lee and Wenner configurations were computed using a digital computer. In general, the larger the sink, the larger the magnitude of the apparent resistivity anomaly up to a sink diameter of about $8a$, for which the apparent resistivity over the central part of the sink is essentially equal to the resistivity of the sink, irrespective of the reflection factor. For sink diameters equal to the electrode separation a, large apparent resistivity anomalies result from "pseudo-focusing" effects. The major peaks of the apparent resistivity curves, which lie outside the edges of the sink for negative reflection factors and inside for positive reflection factors, can be used to detect the edges of the sinks. The album of curves provides a general utility for the qualitative interpretation of apparent resistivity anomalies over features other than hemispherical sinks, such as faults (for large sinks), dikes, grabens, and similar features.

INTRODUCTION

Near-surface geological structures that approximate the shape of hemispherical sinks are often investigated by resistivity methods. For example, resistivity surveys have been made to locate undesirable clay-filled sinks in limestone quarries in western Wisconsin (Kurtenacher, 1934), to explore for mineralized zones that are associated with shallow shale sinks in the Tri-State zinc and lead mining district (Cook, 1954*a* and 1954*b*), and to study bowl-shaped limonite deposits in the West Plains district, Missouri (Meidav et al 1958).

To facilitate the interpretation of field resistivity data over such geological structures, the need of an album of theoretical curves has long been recognized. In a previous paper (Cook and Van Nostrand, 1954), several sets of theoretical horizontal resistivity profiles over hemispherical sinks were given for both the Lee and Wenner configurations. The curves were restricted to one particular reflection factor ($k = -0.6667$) and sink diameter, however, because the computations were tedious and the available tables of the Legendre polynomials were inadequate for the needs of the problem. Since this previous work, the evaluation of the Legendre polynomials and the computations of apparent resistivity curves have been greatly accelerated through the use of digital computers.

The purpose of this paper is to present a comprehensive set of theoretical horizontal resistivity profiles over and near hemispherical sinks that crop out at the surface. The effects of the sink diameter, reflection factor k, and distance of the resistivity traverse from the center of the sink are shown in order to demonstrate the expected characteristics of field curves under a variety of field conditions.

THEORETICAL CONSIDERATIONS

Apparent Resistivity for Lee and Wenner Configurations

Definitions.—The Lee configuration consists of two outer current electrodes C_1 and C_2 that

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† Professor of Geophysics and Head, Department of Geophysics, University of Utah, Salt Lake City, Utah.

‡ Formerly Graduate Student, Department of Geophysics, University of Utah, Salt Lake City, Utah.

[1] Only a few samples of the curves are included in this issue of GEOPHYSICS. A copy of the complete set of curves, as well as the manuscript, can be obtained free of charge by subscribers of GEOPHYSICS and SEG members ($1.00 per copy to others) by writing to the Business Office of the SEG, Shell Bldg., Tulsa, Oklahoma.

are spaced a distance of $3a$ apart (Figure 1). Potential electrodes P_1 and P_2 are so located on the line connecting C_1 and C_2 that they divide the line into three equal segments of length a, which is designated the electrode separation. A third potential electrode, P_0, is placed midway between P_1 and P_2. From the potential differences V_{10} and V_{02} (Figure 1), which are measured between the pairs P_1P_0 and P_0P_2, respectively, the two apparent resistivities ρ_1 (for the right-hand side of the Lee partitioning plane) and ρ_2 (for the left-hand side) are obtained respectively from the equations:

$$\left.\begin{aligned}\rho_1 &= 4\pi a \frac{V_{10}}{I}\\ \rho_2 &= 4\pi a \frac{V_{02}}{I}\end{aligned}\right\}. \tag{1}$$

I is the current flowing between C_1 and C_2.

The Wenner configuration differs from the Lee configuration in that potential electrode P_0 is omitted. From the potential difference V_{12}, which is measured between the pair P_1P_2 (Figure 1), the one apparent resistivity ρ_a is obtained by the equation:

$$\rho_a = 2\pi a \frac{V_{12}}{I}. \tag{2}$$

The station is considered to be the position of P_0 for the Lee configuration (Figure 1) and the midpoint between P_1 and P_2 for the Wenner configuration. The horizontal resistivity profile is obtained by moving the electrode configuration in a straight line, keeping constant the distances between the electrodes. The distance between two successive stations is designated the station interval.

The apparent resistivity, as defined by equations 1 and 2, is equal to the true resistivity for homogeneous ground. In the presence of a disturbing body such as a hemispherical sink, the apparent resistivity is a function not only of the size and resistivity of the sink, but also the geometry of the electrode configuration used. The apparent resistivity usually falls within the ranges of the true resistivities of the materials within the ground over which measurements are made. Due to "pseudo-focusing" effects, however, the apparent resistivity sometimes rises above or falls below the true resistivities of all the materials present. This effect can be seen in many of the theoretical apparent resistivity curves in this paper.

Plotting Apparent Resistivity Data.—In this paper, for both the Lee and Wenner configurations, the ratio of the apparent resistivity ρ_a to the resistivity ρ' of the medium outside the sink is plotted as ordinates. The apparent resistivities on the right and left sides of the Lee partitioning plane are designated by ρ_1 and ρ_2, respectively. In the diagrams, a solid line indicates the values of ρ_1/ρ' and a dashed line indicates those of ρ_2/ρ'. The Lee apparent resistivity values are plotted by the "offset plotting" technique, which is customarily used in the field for the Lee partitioning method. For each station, the value of ρ_1/ρ' is plotted against the position of the midpoint of the line connecting P_0 and P_1 (Figure 1). Similarly, the value of ρ_2/ρ' is plotted against the corresponding position of the midpoint of the line joining P_0 and P_2. It should be emphasized that

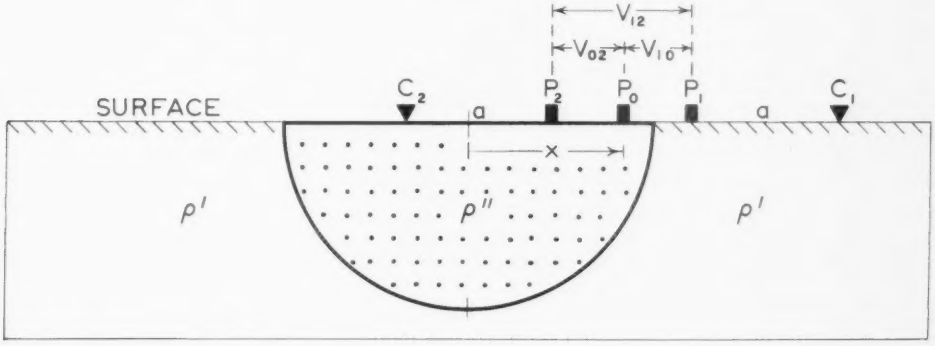


FIG. 1. Lee configuration showing convention of electrode designations and potential differences.

for the Lee configuration, these two values are not plotted against the station at which they are determined, that is, the position of the center electrode P_0.

For the Wenner data, the ratio ρ_a/ρ' is plotted against the station at which the ratio is determined, that is, at the center of the Wenner configuration.

Because it is convenient to use dimensionless quantities, distances along the traverses are plotted in terms of the electrode separation a. Because the ordinates are ratios that are also dimensionless quantities, the apparent resistivity at a given station is obtained by multiplying this ratio by the resistivity (ρ') of the country rock. Since the resulting curves of these plotted ratios can be considered as apparent resistivity curves, the terms "apparent resistivity values" and "values of the ratio ρ_1/ρ' (or ρ_2/ρ', or ρ_a/ρ')" are often used interchangeably in this paper. Strictly, however, the apparent resistivity is equal to the ratio ρ_1/ρ' (or ρ_2/ρ', or ρ_a/ρ') only when the true resistivity ρ' is unity.

Potential Functions.—The apparent resistivities for the Lee and Wenner configurations are readily evaluated from equations 1 and 2, respectively, when the respective potential differences between the proper potential electrodes are known. The total potential at each of the potential electrodes is obtained by superposition of the potentials due to the two current electrodes taken separately. Consequently, from the mathematical and physical standpoints, the basic problem involved is to obtain the potential due to a single point source of direct current in the vicinity of a hemispherical sink. The treatment of this problem involves the solution of Laplace's equation in spherical coordinates, subject to the proper boundary conditions (Cook and Van Nostrand, 1954).

Consider an arbitrary resistivity traverse in plan view in the vicinity of a hemispherical sink of resistivity ρ'' within the surrounding country rock of resistivity ρ' (Figure 2). The potential at electrode P due to a current flowing into the ground through electrode C may be expressed by the following potential functions:

$$U_{1,1} = \frac{I\rho'}{2\pi}\left[\frac{1}{R} + \frac{r_1(\rho'' - \rho')}{r_0 r} \cdot \sum_{n=0}^{\infty} \frac{n}{n(\rho'' + \rho') + \rho''}\left(\frac{r_1^2}{r_0 r}\right)^n P_n(\mu)\right]$$

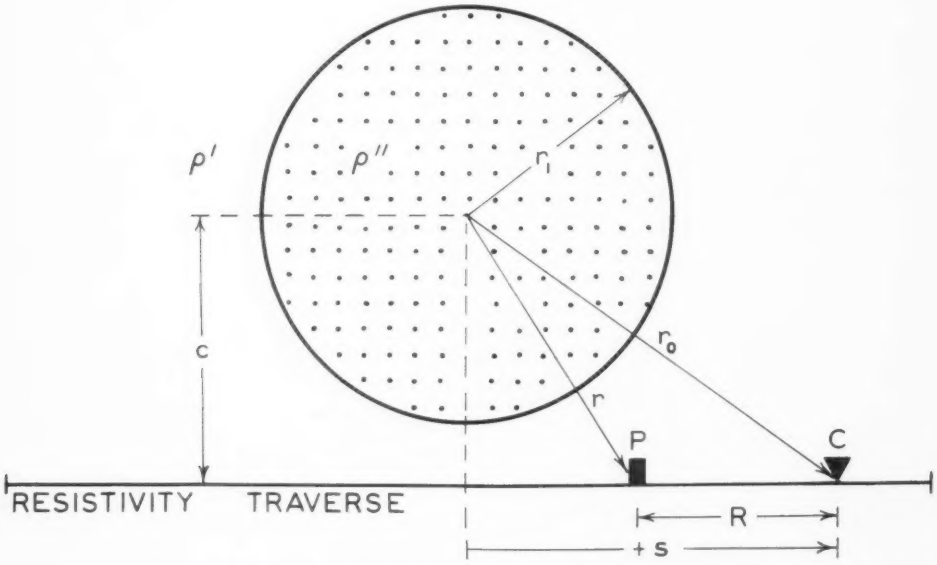


FIG. 2. Plan view of an arbitrary resistivity traverse near a hemispherical sink showing notation used in equations 3 and 4.

$$U_{2A} = \frac{I\rho'\rho''}{2\pi r_0} \cdot \sum_{n=0}^{\infty} \frac{(2n+1)}{n(\rho''+\rho')+\rho''} \left(\frac{r}{r}\right)^n P_n(\mu)$$

$$U_{1B} = \frac{I\rho'\rho''}{2\pi r} \cdot \sum_{n=0}^{\infty} \frac{(2n+1)}{n(\rho''+\rho')+\rho''} \left(\frac{r_0}{r}\right)^n P_n(\mu) \tag{3}$$

$$U_{2B} = \frac{I\rho''}{2\pi}\left[\frac{1}{R} + \frac{(\rho'-\rho'')}{r_1} \cdot \sum_{n=0}^{\infty} \frac{(n+1)}{n(\rho''+\rho')+\rho''} \left(\frac{r_0 r}{r_1^2}\right)^n P_n(\mu)\right]$$

where the notations used are as shown on Figure 2 and where

$$\begin{cases} r = \sqrt{c^2 + (s \pm R)^2} \\ r_0 = \sqrt{c^2 + s^2}. \end{cases} \tag{4}$$

The term $P_n(\mu)$ is the Legendre polynomial with the argument μ expressed as

$$\mu = \frac{r_0^2 + r^2 - R^2}{2r_0 r}.$$

The negative sign in the quantity $(s \pm R)^2$ in equation 4 is used when computing the potential due to C_1 and the positive sign when computing the potential due to C_2. Equations 3 are written in a form convenient for digital computer programming.

The potential functions in equations 3 are for the following cases: U_{1A} is the potential when both P and C are outside the sink, U_{2A} is the potential when P is inside the sink and C is outside the sink, U_{1B} is the potential when P is outside the sink and C is inside the sink, and U_{2B} is the potential when both P and C are inside the sink.

Determination of Apparent Resistivities.—The theoretical apparent resistivities for profiles over and near hemispherical sinks were computed by evaluating equations 3 to determine the potentials at the positions of the various potential electrodes; computing the potential differences V_{10}, V_{02}, and V_{12} by superposition; and computing the apparent resistivities for the Lee and Wenner configurations from equations 1 and 2, respectively. All computations were done on a Burroughs 205 digital computer. A subroutine for the evaluation of the Legendre polynomials was used.

ALBUM OF THEORETICAL CURVES

Approximately 200 theoretical horizontal resistivity profiles over and near hemispherical sinks for the Lee and Wenner configurations are shown in Figures 5 to 43 for various sink diameters, reflection factors, and distances of the resistivity traverses from the center of the sinks.[2] The sink diameters vary from $16a$ to $0.5a$, a being the electrode separation. The distances of the traverses from the center of the sink are at various intervals between zero and $1.25r_1$, where r_1 is the radius of the sink. The reflection factor k, which is defined (Roman, 1933) by the equation

$$k = \frac{\rho'' - \rho'}{\rho'' + \rho'}$$

Table 1. Sink Resistivity for Various Values of Reflection Factor k. Resistivity of Country Rock ρ' Is Equal to Unity

$k = (\rho'' - \rho')/(\rho'' + \rho')$

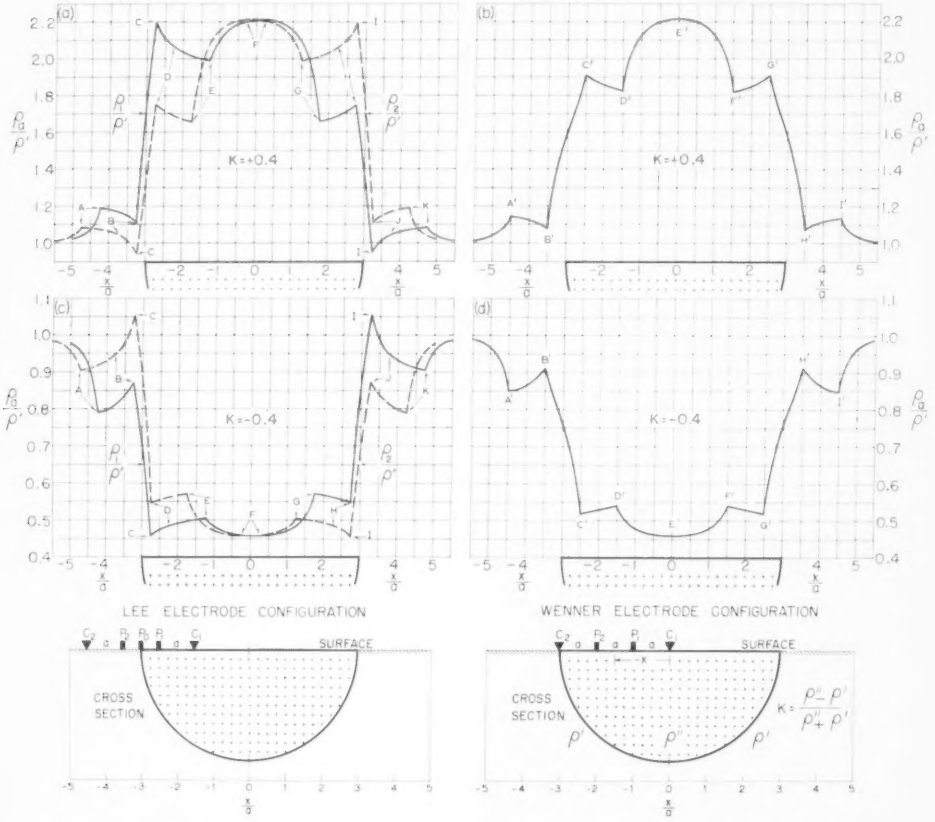
Relative Resistivity of Sink	Reflection Factor k	Sink Resistivity ρ''
Perfect insulator	+1.0	∞
More resistive than country rock	+0.9	19.000
	+0.8	9.000
	+0.7	5.667
	+0.6	4.000
	+0.5	3.000
	+0.4	2.333
	+0.3	1.857
	+0.2	1.500
	+0.1	1.222
Same resistivity as country rock	0	1.000
Less resistive than country rock	−0.1	0.818
	−0.2	0.667
	−0.3	0.538
	−0.4	0.429
	−0.5	0.333
	−0.6	0.250
	−0.7	0.176
	−0.8	0.111
	−0.9	0.053
Perfect conductor	−1.0	0

[2] Some of the Figures mentioned in this paper are not included here, but are included in the complete set of curves. The procedure for obtaining a complete set of these curves is given in footnote 1.

varies from -0.8 to $+0.8$. Table 1 shows the conversion of values of reflection factors, taken at intervals of 0.1, into values of resistivity of a sink of resistivity ρ'' in relation to the resistivity of the surrounding country rock ρ', which for convenience is taken as unity. It will be noted that sinks are more resistive than the country rock for positive reflection factors and less resistive for negative reflection factors.

Important Features of Curves

Several diagnostic features of the theoretical curves characterize the edges and center of hemispherical sinks and aid in the interpretation of field curves. Figure 3, which shows theoretical horizontal resistivity profiles over the center of hemispherical sinks of diameter $6a$ and reflection factors ± 0.4, can be used as an example to describe these features. The various discontinuities



A Current electrode C_1 crosses left edge of sink.
B Potential electrode P_1 crosses left edge of sink.
C Potential electrode P_0 crosses left edge of sink.
D Potential electrode P_2 crosses left edge of sink.
E Current electrode C_2 crosses left edge of sink.
F Configuration symmetrical about center of sink.
G Current electrode C_1 crosses right edge of sink.
H Potential electrode P_1 crosses right edge of sink.
I Potential electrode P_0 crosses right edge of sink.
J Potential electrode P_2 crosses right edge of sink.
K Current electrode C_2 crosses right edge of sink.

A′ Current electrode C_1 crosses left edge of sink.
B′ Potential electrode P_1 crosses left edge of sink.
C′ Potential electrode P_2 crosses left edge of sink.
D′ Current electrode C_2 crosses left edge of sink.
E′ Configuration symmetrical about center of sink.
F′ Current electrode C_1 crosses right edge of sink.
G′ Potential electrode P_1 crosses right edge of sink.
H′ Potential electrode P_2 crosses right edge of sink.
I′ Current electrode C_2 crosses right edge of sink.

FIG. 3. Theoretical horizontal resistivity profiles over center of hemispherical sinks with Lee and Wenner configurations for reflection factors $k = \pm 0.4$, showing correlation between discontinuities of slopes of the curves and locations of station. Diameter of sink $= 6a$. Offset plotting for Lee configuration.

in slope of the curves that occur as each electrode crosses the edge of a hemispherical sink are shown in the figure. Of these many discontinuities, the most important for interpretation for negative reflection factors are (1) the high peaks at C and I (Figure 3c) and the peaks immediately below them, all four peaks of which lie a distance of $a/4$ outside the edges of the sink for the Lee configuration, and (2) the pronounced peaks at B' and H' (Figure 3d) which lie a distance of $a/2$ outside the edges of the sink for the Wenner configuration. Similarly, the most important peaks for positive reflection factors are (1) the high peaks at C and I (Figure 3a) and the peaks immediately below them, all four peaks of which lie a distance of $a/4$ inside the edges of the sink for the Lee configuration, and (2) the pronounced peaks at C' and G' (Figure 3b) which lie a distance of $a/2$ inside the edges of the sink for the Wenner configuration. These pronounced peaks are diagnostic in detecting the edges of sinks. Over the central portion of hemispherical sinks, the magnitude of the apparent resistivity curves is usually high for positive reflection factors and low for negative reflection factors. For a station exactly over the center of any hemispherical sink, irrespective of the size or reflection factor, each of the offset plotted values of the apparent resistivity for the Lee configuration is equal to the apparent resistivity value for the Wenner configuration.

Magnitude of Anomalies.—The anomaly index (Cook and Van Nostrand, 1954, p. 772) can be used conveniently to compare the relative magnitude of the apparent resistivity anomalies. In analysis of theoretical data, the anomaly index is defined as the maximum value of ρ_a/ρ' minus the minimum value of ρ_a/ρ' for the Wenner configuration. For the Lee configuration, ρ_a is replaced by either ρ_1 or ρ_2 in the definition. The sign of the anomaly index is arbitrarily assigned negative for the negative reflection factor domain and positive

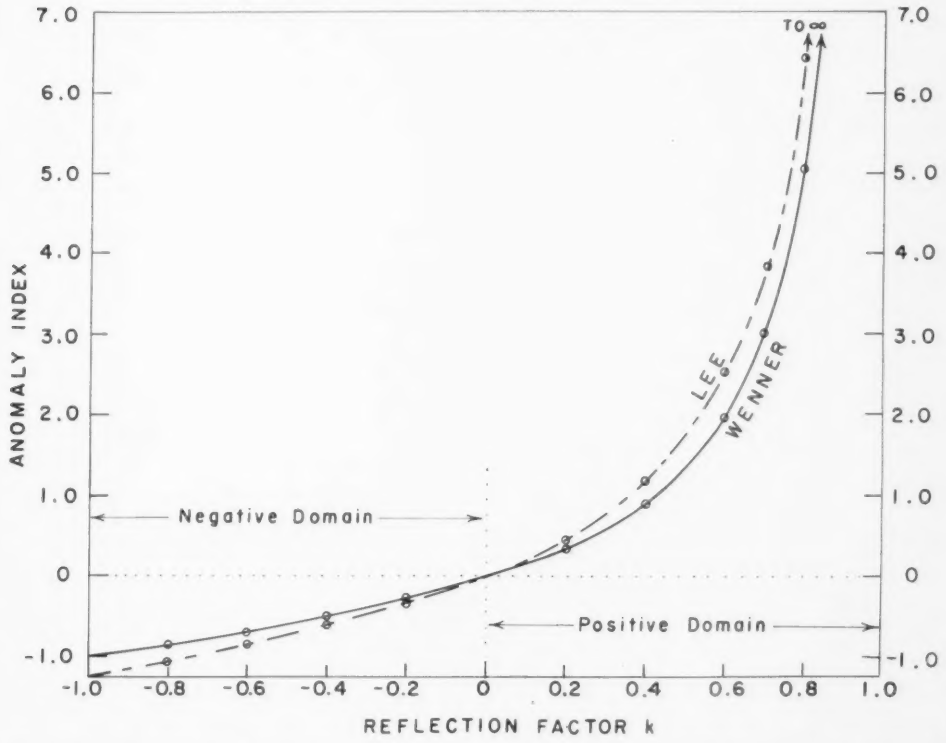


FIG. 4. Anomaly index plotted against reflection factor k for theoretical horizontal resistivity profiles for Lee and Wenner configurations over center of hemispherical sinks with diameter $4a$. $k=(\rho''-\rho')/(\rho''+\rho')$.

for the positive reflection factor domain.

Table 2 gives the anomaly indices for sinks with different diameters for profiles over the center of the sinks. The magnitudes of the anomalies over sinks for the Lee configuration are greater than those for the Wenner configuration. This fact is demonstrated by the observation in Table 2 that the ratio of the anomaly index of the Lee configuration to that of the Wenner configuration is greater than unity.

It should be emphasized that all comparisons of anomaly indices should be restricted either solely to the domain of positive reflection factors or solely to the domain of negative reflection factors. If comparisons are attempted for the anomaly indices between positive and negative reflection factor domains, an erroneous impression will be given that larger anomalies occur over sinks with positive reflection factors than negative reflection factors.

Effect of Sink Diameter.—Certain generalizations can be made concerning features of the profiles over the center of sinks with diameters of a or greater (Figures 5 to 8). For sinks with a negative reflection factor, the smaller the sink, the shallower is the apparent resistivity trough and the higher are the apparent resistivity peaks that lie outside the sink. For sinks with a positive reflection factor, the larger the sink, the higher is the apparent resistivity crest over the center of the sink and the more nearly the apparent resistivity approaches the resistivity of the sink.

Table 2. Anomaly Indices for Profiles Through the Center of Sinks with Various Diameters

Reflection Factor k	Sink Diameter	Anomaly Index		
		Wenner	Lee	Ratio Lee /Wenner
+0.6	$16a$	2.984	3.002	1.006
	$12a$	2.963	2.998	1.012
	$8a$	2.875	2.930	1.019
	$6a$	2.702	2.780	1.029
	$4a$	1.966	2.529	1.286
	$2a$	0.651	1.632	2.507
	a	0.630	.800	1.270
	$0.5a$	0.217	.547	2.521
−0.6	$16a$	−0.749	−0.780	−1.041
	$12a$	−0.747	−0.786	−1.052
	$8a$	−0.738	−0.798	−1.081
	$6a$	−0.722	−0.805	−1.115
	$4a$	−0.654	−0.824	−1.287
	$2a$	−0.576	−0.938	−1.628
	a	−0.920	−1.140	−1.239
	$0.5a$	−0.331	−0.881	−2.662

For a sink with a diameter that is large (as for example, $16a$) in comparison with the electrode separation (Figures 5a and 6a) the edge effects of the sink approximate those caused by a vertical fault (see Figures 8d and 9d, Cook and Van Nostrand, 1954). The only apparent differences are that the magnitudes of the peaks lying outside the sink with negative reflection factor are lower for the faults than for the sinks, and the magnitudes of the peaks lying inside the sink with positive reflection factor are higher for the faults than for the sinks (Figures 7a and 8a). Also, for such a sink, the apparent resistivity over the center of the sink is essentially equal to the resistivity of the sink.

For sinks with diameters of about $4a$ or greater, the apparent resistivity curves are similar in appearance, except that the magnitudes differ.

For sinks with diameters of about $2a$ or less, generalizations concerning the character of the curves are difficult to make. The curves often comprise a complex array of peaks and troughs. For sinks with diameter of $2a$ and positive reflection factors (Figures 7f and 8f), a high symmetrical peak occurs near either edge of the sink; these unusually pronounced peaks would assist in the discovery of such sinks but might lead to an erroneous interpretation unless their existence were anticipated. Similar anomalous peaks are observed over vertical dikes of width $2a$ (Van Nostrand and Cook, manuscript in preparation for publication). For sinks with diameter of a (Figures 5f, 6f, 7e and 8e), the striking peaks (for negative reflection factors) and sharp lows (for positive reflection factors) lying outside the edges of the sink occur when both a current and potential electrode are on opposite edges of the sink simultaneously; and the phenomenon is attributed to the current-converging effect for the former and current-diverging effect for the latter. These effects also result in the unusually high anomaly indices in Table 2 for a sink with diameter of a.

For sink diameters of $0.5a$ (Figures 37, 38, and 43), the apparent resistivity anomalies are relatively small. The resistivity curves are complex and show many sharp peaks and troughs. The shapes of the anomalies are similar to those resulting from "field noise." These curves can be used to study the effects of such localized features as boulders and holes along the traverse.

Effect of Reflection Factor.—Qualitatively, the

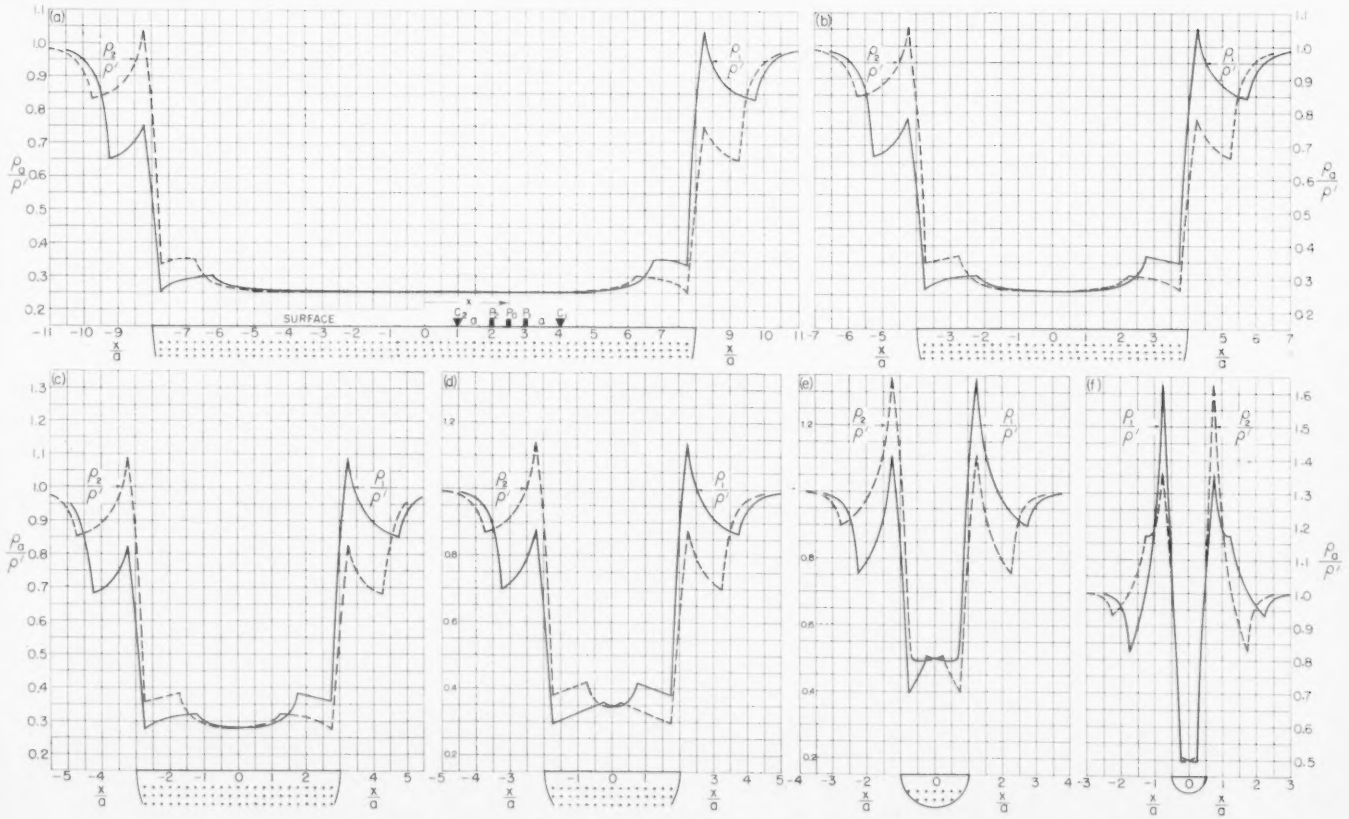


FIG. 5. Theoretical horizontal resistivity profiles over center of hemispherical sinks with different diameters: (a) $16a$, (b) $8a$, (c) $6a$, (d) $4a$, (e) $2a$, and (f) a, Lee configuration (offset plotting). Reflection factor $k=(\rho''-\rho')/(\rho''+\rho')=-0.6$.

FIG. 7. Theoretical horizontal resistivity profiles over center of hemispherical sinks with different diameters: (a) $16a$, (b) $8a$, (c) $6a$, (d) $4a$, (e) a, and (f) $2a$, Lee configuration (offset plotting). Reflection factor $k=(\rho''-\rho')/(\rho'+\rho')=0.6$.

effect of reflection factor upon the magnitude and shape of the apparent resistivity curves is shown in Figures 39 to 42 which are families of curves for Wenner profiles over the center of sinks with reflection factors ± 0.8, ± 0.6, ± 0.4, and ± 0.2.

Quantitatively, the effect of reflection factor upon the magnitude of the apparent resistivity curves can be shown by plotting the anomaly index as ordinate against the reflection factor as abscissa, as is shown in Figure 4. In the positive reflection factor domain, the values of the anomaly index increase in an exponential-like manner with increasing values of reflection factor and approach infinity as the reflection factor approaches plus one. In the negative reflection factor domain, the values of the anomaly index increase negatively in an approximately linear manner with increasingly negative values of the reflection factor.

Effect of Distance of Traverse from Center of Sink.—For traverses that are taken progressively between the center and the edge of any given sink, the overall magnitude of the apparent resistivity anomaly progressively diminishes; the

distance between the flanks of the main troughs or crests of the apparent resistivity curves become progressively smaller; and the major peaks are progressively dampened, but usually maintain themselves until the traverse is tangent to the edge of the sink. For traverses lying outside of the sink, the apparent resistivity anomaly usually diminishes rapidly. For a traverse lying at a distance outside of the edge of a sink equal to the radius of the sink, the anomaly is about the same magnitude as for field noise; and this constitutes the limiting detectability of a sink (Cook and Van Nostrand, 1954, p. 787). Figures 19f and 20f show examples of the low anomalies obtained on traverses at a distance of $1.25r_1$ from the center of the sink; in this case the anomaly is about 6 percent of the total anomaly obtained over the center of the sink.

CONCLUSIONS

The album of theoretical horizontal resistivity profiles presented in this paper shows the effects of sink diameter, reflection factor, and distance of the traverses from the center of a hemispherical sink upon the magnitude and shape of the curves. The selection of reflection factors of ± 0.8, ± 0.6, ± 0.4, and ± 0.2 for many of the sinks, as well as the selection of various diameters ($16a$, $8a$, $6a$, $4a$,

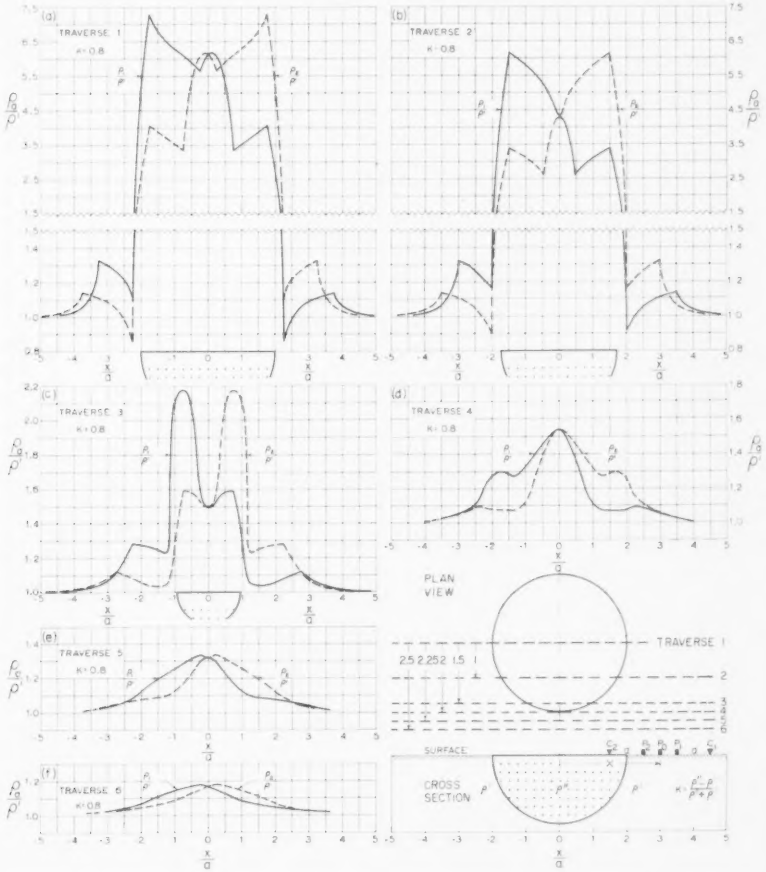


FIG. 19. Theoretical horizontal resistivity profiles over hemispherical sink at different distances from center of sink, Lee configuration (offset plotting). Cross-sections taken along resistivity traverses. Diameters of sink=$4a$. Reflection factor k=0.8. (Correction noted in proof: in "plan view" diagram, "1.5" for distance to traverse 3 should read "1.75."

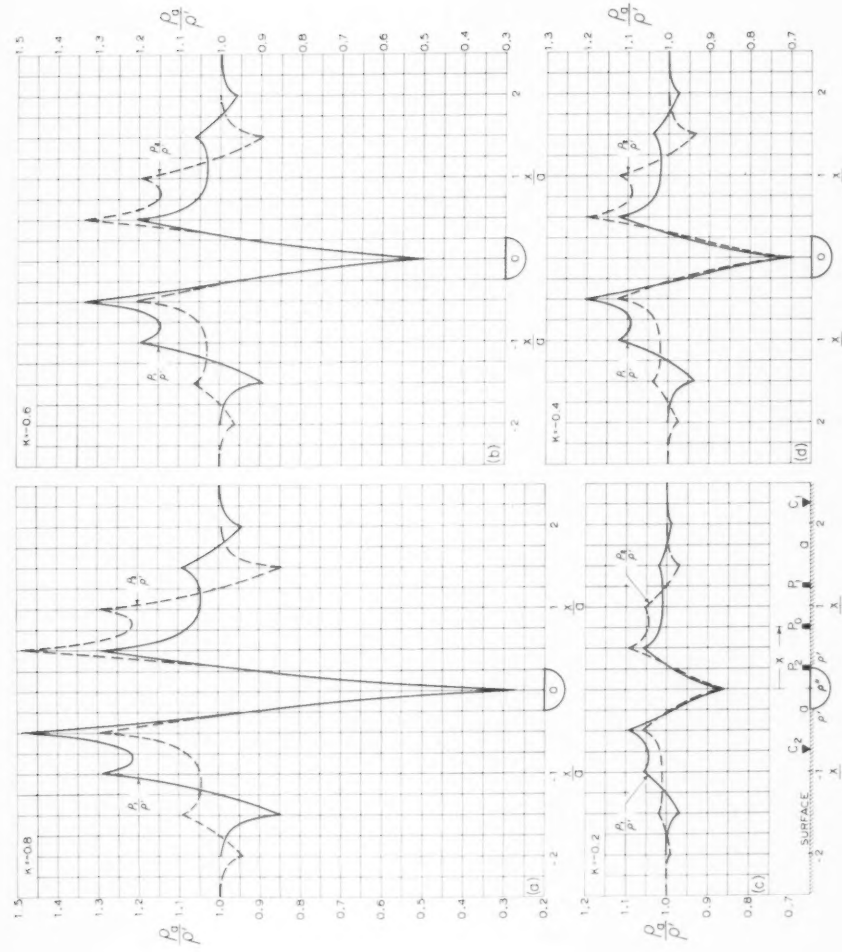


FIG. 37. Theoretical horizontal resistivity profiles over center of hemispherical sinks with diameter $0.5a$, Lee configuration (offset plotting). Reflection factors $k=(\rho''-\rho')/(\rho''+\rho')=-0.8$, -0.6, -0.4, and -0.2.

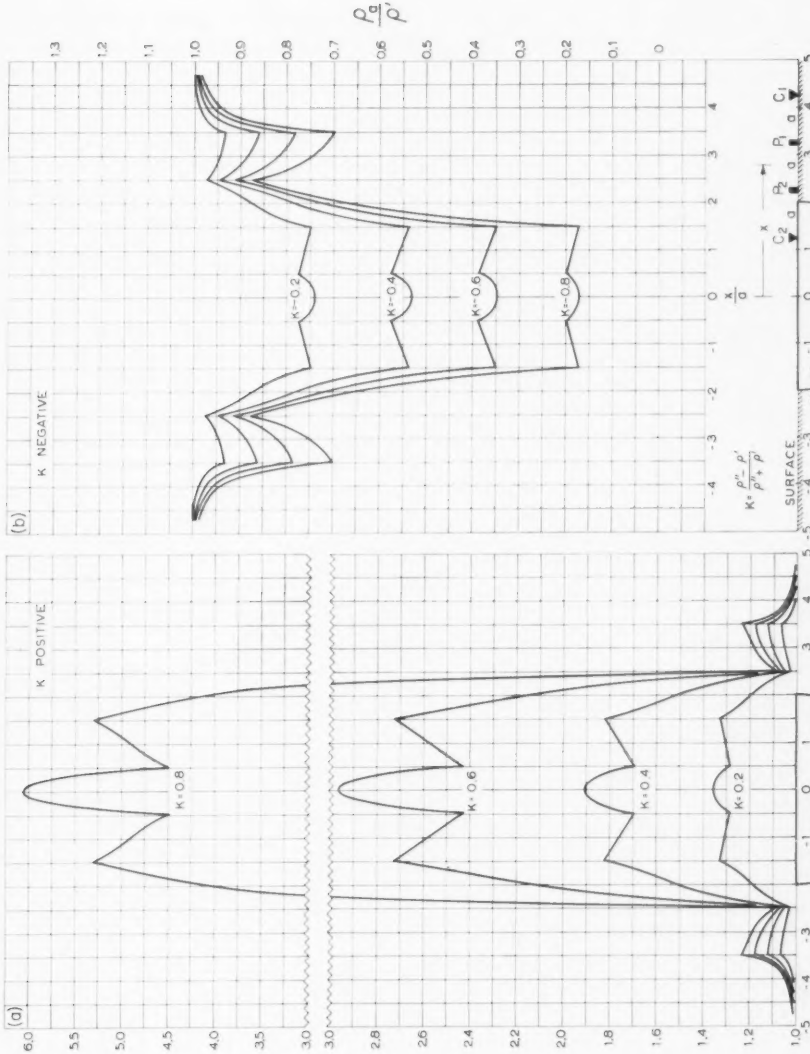


FIG. 40. Theoretical horizontal resistivity profiles over center of hemispherical sinks with diameter $4a$, Wenner configuration. Reflection factors $k = \pm 0.8$, ± 0.6, ± 0.4, and ± 0.2.

$2a$, a, and $0.5a$), permit a comparison of the theoretical curves with a wide variety of field conditions.

In general, the larger the sink, the larger is the magnitude (up to a sink diameter of about $8a$) and width of the apparent resistivity anomaly. For sink diameters greater than about $8a$, the apparent resistivity over the central part of the sink is essentially equal to the resistivity of the sink, irrespective of the reflection factor; and the edge effects of the sink, which comprise major peaks that are diagnostic in locating the edges of the sink, are essentially the same as those over a corresponding vertical fault. For sink diameters of about $4a$ and greater, the apparent resistivity curves are similar in appearance, except that their magnitudes differ. For sink diameters of about $2a$ or less, generalizations are difficult, as the curves consist of complex arrays of peaks and troughs, which are dependent on the size of the sink. For sink diameters of a, large apparent resistivity anomalies result from current converging effects for negative reflection factors and current diverging effects for positive reflection factors. Anomalies over sinks with a diameter of $0.5a$ simulate the effects of large boulders and other materials that contribute to the background "noise" in a field resistivity survey.

The major flanking peaks of apparent resistivity curves can be used to locate the edges of the sink. For negative reflection factors, the peaks lie at distances of $a/4$ and $a/2$ outside the edges of a sink for the Lee and Wenner configurations, respectively; and for positive reflection factors the peaks lie at distances of $a/4$ and $a/2$ inside the edges of a sink for the Lee and Wenner configurations, respectively.

The apparent horizontal resistivity profiles for traverses at various distances from the center of the sink show that the nearer the traverse is to the center of the sink, the larger is the anomaly. Also these profiles confirm the fact that for any reflection factor, the magnitude of the anomaly at a distance from the center of the sink that is equal to the sink diameter would be of a magnitude comparable with the field noise, and therefore at this distance the sink would not generally be detectable.

A study of the theoretical curves and anomaly indices over hemispherical sinks with various diameters and reflection factors shows that the apparent resistivity anomalies for the Lee configuration are greater and afford more diagnostic information than the corresponding anomalies for the Wenner configuration.

The album of curves provide a general utility for a qualitative interpretation of apparent resistivity anomalies over features other than hemispherical sinks, such as faults (for large sinks), dikes, grabens, and similar features.

ACKNOWLEDGMENTS

Appreciation is expressed to Dr. Robert G. Van Nostrand, Chief Geophysicist, Société de Prospection et Exploitations Pétrolières en Alsace, Paris, France, for advice incident to theoretical aspects of the problem. Mr. J. F. Rice and Miss Dee Morgan, University of Utah Computer Center, gave advice and assistance in programming the computer. Financial support from the University of Utah Research Fund was given for this study in the form of a fellowship to the junior author.

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CURRENT AND FUTURE PARAMETERS IN GEOPHYSICS*

RICHARD A. BAILE†

A seeming paradox of our time is the continued decline in use of geophysical effort while constant and steady improvement of the tool is being achieved. Seismic crew effort in the United States declined from an all time high of 710 in 1952 to 395 in the fall of 1958—a 44 percent decline! Patrick (1960). In 1958 for the first time the United States used less than 50 percent of the world effort.

There is no doubt but that improvement has been achieved, particularly during the last decade, with the commonplace use of magnetic tape recording, multiplicity of holes and geophones and the continuous velocity log, a tool which has gained wide acceptance by exploration personnel. This multi-purpose tool, known industry-wide as "Sonic" or "Acoustic" log, represents a primary advance in petroleum exploration, since it provides a direct study of sound characteristics where it counts—in the borehole, thus providing an excellent foundation for further advancement of geophysical tools. Moreover, the development of energy sources other than explosives confined in a borehole, such as the weight drop, has further enhanced the oil-finder's ability to delineate prospects. Of lesser magnitude, yet important to the industry, we have witnessed the evolution of many ideas into practical use. The development of Ammonium Nitrate as a seismic explosive has reduced our explosive costs by as much as 60 percent in some areas. "Sausage" powder and delay caps have made important contributions to the improvement of data as these means tend to minimize the recording of secondary or "ghost" reflections. The "percussion bit" as adapted to ordinary shot hole drills, reduces our cost in the areas where hard surface rocks are encountered.

Another avenue of change is occurring in the onset of various type crews employed. This is manifested in labor crews, "bob-tail" crews and other combinations of company and contractor personnel and equipment. The reasons for this are obvious, the main one being to create the more efficient use of personnel and equipment. We shall see a lot more of this in the future.

Continued effort in research is being expended on geochemical, electrical, and radioactive methods. These methods, though little used, still represent tools of exploration which must not be discounted.

Still, we as oil exploration people face a greater challenge today than we did ten years ago. We are responsible for developing a program adequately to satisfy an anticipated world-wide demand of 50 million barrels of oil per day by 1975. With current reserves estimated at 260 billion barrels of oil, and without added discovery, we could in all probability exhaust these reserves by 1975. The atomic energy position, now and in the future, is one of great expense. Oil shales, though ultimately to be utilized, are also expensive. It is apparent then, that we must continue our search with increased effort if we are to maintain our present competitive position as prime suppliers of energy.

With this tremendous challenge ahead of us, why are our positions less secure than they were a decade or so ago?

One thing is certain, we cannot place the responsibility for this situation on technology. Technology will rise to the cause faster than man, if allowed to do so. Witness our current space age activity. Look at what the communication people have accomplished. You see in these ef-

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† Empire Geophysical, Inc., Midland, Texas.

forts a tremendous technological advance. Where, then, is the cause for our situation to be found? The cause is simple—economics. Simply stated, the return on investment in exploring for oil in the U. S. is poor. The solution lies in maintaining petroleum competitive with other energies and keeping the U. S. competitive with other producing areas—we have to provide the product at a competitive rate. Exploration is the key to meeting this challenge.

Four prime factors are set up for consideration as to how they relate to satisfying this objective.

(1) Exploration Planning.
(2) Exploration Personnel.
(3) Exploration Research.
(4) Exploration Stability—The key to effective growth.

EXPLORATION PLANNING

There is no question that exploration planning is often thwarted by the variation in money that is available. But, let us not use this as a criterion for our planning. Rather, plan to expend the money made available in the most efficient and wise manner. How do we accomplish this? It goes without saying that we must develop some first class prospects. Grade them in order of preference. Have a few extra areas in the desk—you never know when one of the first class prospects may "blow up" for some reason. Develop these areas with long range thinking,—we do not always have to drill the area during the year it was conceived. It may take ten years before the land situation and other developments are right for testing the area. Finally, be bold in your planning.

Once we have selected an area, the next order is to use all members of the exploration team to explore the prospect on paper. Have a precise understanding of the objective. From this, we shape the program to overcome adverse factors. Establish clearly the part each individual is to assume. Set up performance standards to gauge the success of the program at regular intervals. Study the economics of the area. Following this, you decide that the situation merits geophysical coverage. You now have a first class prospect planned, organized, and ready to submit to management. Through combined efforts of all on the exploration team, you have a package that will "sell", management is impressed, and you are cleared to proceed.

A seismic crew is assigned. As the field work commences, we reach another critical stage.

First of all, let us dissolve this idea that a seismograph crew is something that can be used like a well logging service, i.e., one day and through. We have a tendency to forget that the average crew consists of 16 to 18 men, 10 to 12 units, and costs an average of $1,800.00 per day to operate. For a crew to accomplish the objective we have previously outlined, we must give it the opportunity to gain momentum,—to become familiar with the objective. They cannot do this in one day. If the nature of your work is such that it consists of short program on an intermittent basis, then, first, plan sufficient coverage to evaluate the area properly and, second, try to include as many areas as possible within reasonable distance limits for the crew to process during a continuing working period. By having more than one area to process, you can work between the areas to obtain economically the necessary detail work once the initial program is completed. These considerations are important to all concerned, because only in this manner can you obtain the desired degree of economy and efficiency from a crew. If one single item of the above needs more emphasis than the others, I would say that the planning of sufficient program to evaluate the prospect during the initial entry into the area by the crew is the most important. We have witnessed time and again the results of insufficient coverage. One instance led to the drilling of a dry hole because of failure to shoot an additional mile of program. In contrast, we have observed where a significant oil field was missed because of unwillingness to cover the area thoroughly. There is no substitute for good planning relating to the programming of a geophysical crew.

As the work progresses, make periodic and complete checks to see that the objective is being accomplished. If it is not, then take steps to remedy. If this fails, abandon the project as far as attempting to evaluate it by the geophysical method initially employed. There is no justification for a continued program which fails to produce results.

Assuming success in evaluating the area, you are now ready to reassemble the exploration team for the preparation of your recommendation. Once again we emphasize that all members of the team have an opportunity to contribute to the preparation of the recommendation.

What have we accomplished through planning?

We have taken the first and most important step toward our objective—the economical use of talents and equipment.

EXPLORATION PERSONNEL

Another problem facing the exploration group is—from whence are our heirs coming? Who is going to handle the work 20 and 30 years from now? At first reckoning, this does not seem to a problem with so many professional oil people looking for work. However, consider an example cited recently by Lewis Weeks, AAPG Past President, where he noted a class in geology, at a leading geological school, registering 6 students in place of the normal size of 60 to 70 students. At this rate, we will be in desperate need of geologists and geophysicists by 1965. Going further, consider the climate we have generated in trying to develop competent field men during the past few years. We move him and his family on an average of three to five times a year. His hourly pay is considerably below that of an average industrial worker. In order that he may earn sufficient income, he is scheduled to work between 50 and 70 hours per week. On an average, his benefits in the way of retirement income, etc., are at a minimum level. How can we develop and retain competent field men under these circumstances?

If we fail in this important function of providing incentive for young men in college to pursue the earth sciences and fail to provide a suitable climate for our field men, we have dealt a crippling blow to our effort to meet our objective.

EXPLORATION RESEARCH

We must intensify our exploration research and development program. To think that the reflection seismograph in its present form should be one of the dominant tools for exploration in 1975 is ridiculous! But, it may well be if we fail to provide funds and talent to carry on a soundly guided research program. The geophysical contractors are anxious to carry on research programs but are greatly limited because of lack of funds. Because of this, it is no wonder that the amplifiers and geophones in use today are essentially the same as ten years ago. As a matter of fact, the current economic condition is in many instances, forcing the contractor to "cannibalize" his equipment in order to stay in business, in spite of the fact that he is providing approximately 64 percent of the total geophysical effort in the free world today. When this becomes the case, we are failing, again, to provide the climate so essential to our objective. To cite an example—there is a big field ahead of us in frequency and amplitude resolution. The knowledge we gain through working with the continuous velocity log will be of great aid in our ability to develop successful methods employing frequency and amplitude resolution as a means of isolating favorable prospects. Once we overcome this problem, we should be able to initiate programs successfully to do stratigraphic studies by the seismic method.

As to advances in interpretation, we must make significant strides in the resolution of data if we are to continue to exploit all the resources at hand and those to come in the future. Today, we are afforded the benefits of tape recording. Digital computing is rapidly being accepted. Our coordination of geological and geophysical thinking is progressing.

EXPLORATION STABILITY

We should consider at this time the premise on which the three factors of planning, personnel and research may be realized—Exploration Stability.

First, we find no one who feels that our industry is becoming obsolete and no longer a vital part of the U. S. economy. In fact everyone agrees that we have an important function to perform. Second, we all seem to agree that exploration is the key to opening the first door on our way toward satisfying our objective. After all, we cannot supply the product for very long if we fail to uncover additional reserves. Third, the science of geophysics provides the means by which explorationists can search the surface of the earth for additional reserves. However, today we have failed to continue sufficient improvement in the science to justify its use by industry on the scale previously experienced. This poor situation stems from the simple rule of economics—when risk exceeds reasonable hopes of return, the object of the risk is abandoned. Now this usually occurs by area, and the U. S. is the area today. I dare say, that without import controls the use of geophysics would even be at a lower ebb than that we are experiencing in this country today. Hence, to search economically for oil, we must develop a better tool. You can only go so far in improving the efficient use of existing tools. To develop a better tool, we must provide a basis on which such may be done. We cannot do this when we

experience the fluctuation in crew activity and exploration personnel as we have during the past few years, because this fluctuation weakens the foundation on which to build. I doubt that we can come up with a research program such as A.T.&T., for their future market is continually increasing; thus, their income position is essentially established. But, we should point in this direction. If the contractor could have some assurance of his future income position, I feel that competition among these people would lead to a great increase in research and development, hence the development of better tools. We must achieve stability in effort or we are endangering the future of our profession.

Finally, but certainly not least, we must avoid negative thinking in our search for oil. It was not too long ago when we emphatically stated that there was no pre-Penn. oil in the Paradox Basin. Negative thinking is born in fear—fear of being wrong. Far too many of us are content to ride with the crowd. We are willing to follow—not lead. We must not hedge on our convictions. If we are wrong, then profit from these mistakes—it is in this manner we learn.

We say oil in the U. S. is a bargain and I am sure it is, but oil outside our United States is a better bargain. We cannot afford to let this discrepancy become too great. This is even more important to us since oil's position in the energy picture is being challenged by other fuels.

A brighter future for our profession is not inevitable. We must not lie back and hope for the great increase in demand to solve our problems. Our future depends entirely on our ability to give better values.

These are the future parameters in geophysics. If we fail in satisfying these objectives then we hasten the day when petroleum becomes obsolete.

GEOPHYSICS, VOL. XXVI, NO. 3 (JUNE, 1961), PP. 359-373, 19 FIGS.

WICHITA MOUNTAINS SEISMOLOGICAL OBSERVATORY*

M. G. GUDZIN† AND J. H. HAMILTON†

INTRODUCTION

The Wichita Mountains Seismological Observatory was engineered and is now being operated under the technical supervision of the Air Force Technical Applications Center (AFTAC) by The Geotechnical Corporation of Garland, Texas. The work is being performed as a part of Project VELA Uniform, under the overall direction of the Advanced Research Projects Agency (ARPA). The seismological equipment used is identical to that recommended in 1958 by the Conference of Experts for detecting violations of a possible agreement on the suspension of nuclear tests. The equipment recommended is quoted in Appendix I attached to this report. This is the first station to be built employing the recommended instrumentation and the capabilities of a control system using such instrumentation have not been determined. The observatory's performance should be of great interest to delegates of the United States, United Kingdom, and U.S.S.R. who are currently negotiating in Geneva for a ban on nuclear testing.

The new observatory is located in the foothills of the Wichita Mountains, about fifteen miles northwest of Lawton, Oklahoma. The site is located on the map shown in Figure 1. It was selected because of the low microseismic background in the region and because of the availability of buildings and vaults in the area which greatly reduced the time required to establish the observatory.

The term "seismometer" in this report refers only to the detector that senses the earth motion and does not include the amplifier or recorder. The term "seismograph" refers to the detector, including the amplifier and recorder. The term "seismogram" refers to the resulting record.

LAYOUT OF THE OBSERVATORY

Figure 2 shows a pictorial diagram of the layout of the observatory. A total of ten vaults covered with earth can be seen in the illustration. The four large vaults shown in the upper part of the diagram are constructed of concrete and contain the narrow-band and broad-band seismometers specified in the appendix and four of the ten seismometers in the array. The other vaults are water-tight cans located in a shallow excavation and contain the remaining six seismometers of the array. Approximately two feet of earth is piled over the cans to protect the instruments from temperature changes. The data from the seismometers located in each of the vaults is transmitted to the amplifiers located in the small building, and then to the larger central-recording building.

Figure 3 shows a scale layout of the vault pattern. This pattern was selected because it was the pattern that could be constructed most easily considering existing vaults, cables, buildings, rock outcrops, accessibility, and other factors. It is thought that a pattern of ten seismometers forming a series of equilateral triangles might be preferable and the array may later be changed to this configuration. All seismometers were placed on the granitic bedrock that occurs in the area. The background noise level is approximately two millimicrons peak-to-peak (0.000,002 mm) at a period of one second. The spacing of the seismometers in the array is approximately two thousand feet.

* Manuscript received by the Editor November 7, 1960.

† Geotechnical Corporation built and is operating the observatory for the Advanced Research Projects Agency under a contract administered by the Air Force Technical Applications Center.

FIG. 1. Location of Wichita Mountains Seismological Observatory.

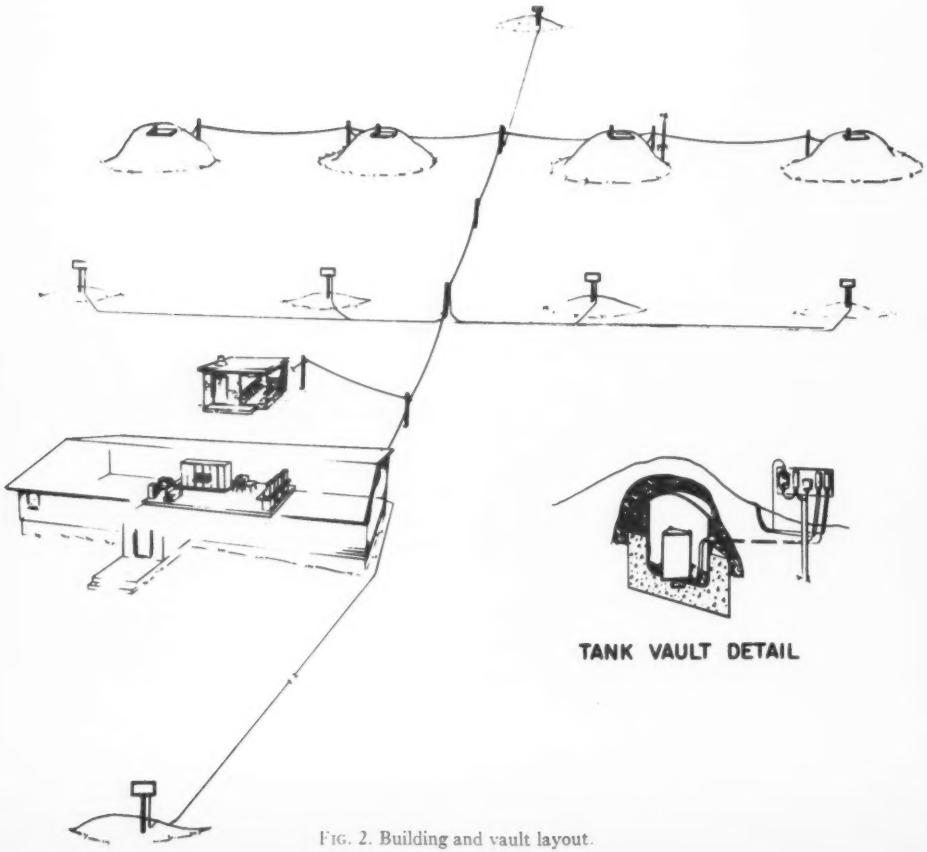
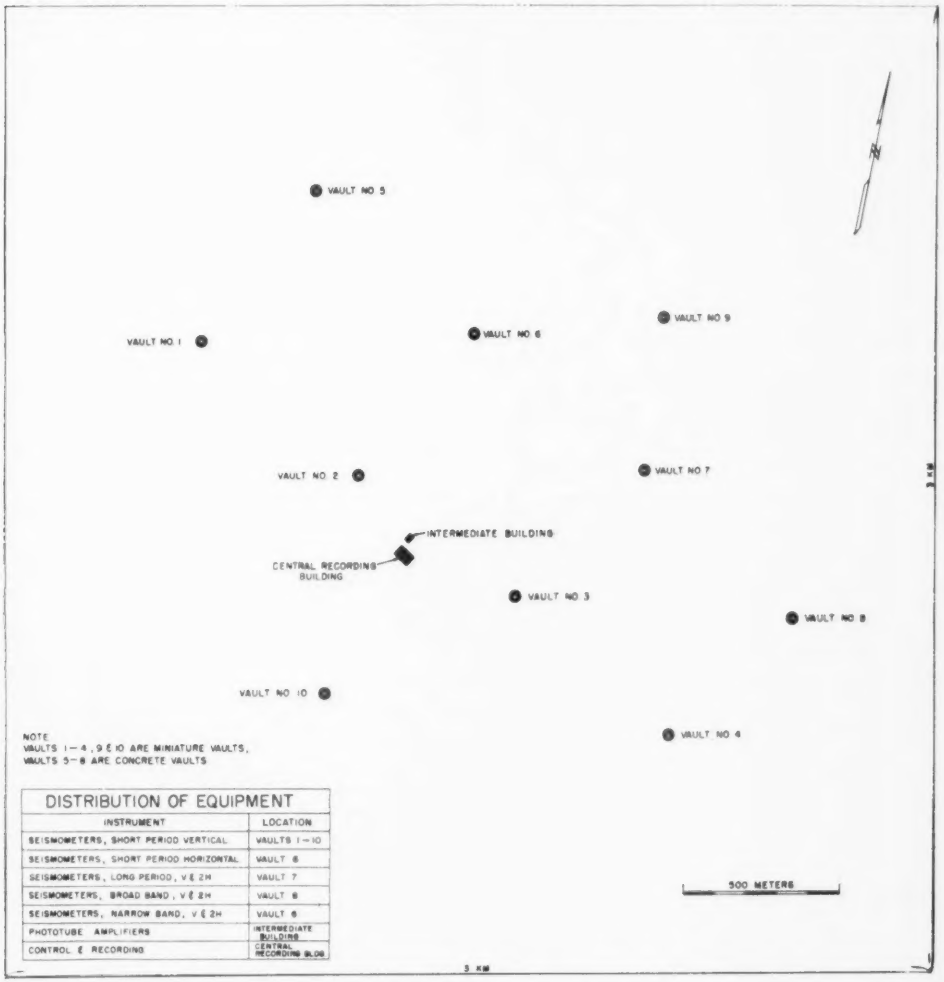


FIG. 2. Building and vault layout.

Figure 4 shows a block diagram of the instrumentation. The ten-element array, the three-component short-period seismograph, the three-component broad-band seismograph, the three-component narrow-band seismograph, and the three-component long-period seismograph require a total of 21 seismometers. One of the vertical seismometers of the ten-element array also serves as the vertical component for the three-component short-period seismograph. The seismometers are located in ten separate vaults and drive phototube amplifiers located in the amplifier building near the central recording. The output of the amplifiers is routed through the data control units and recorded on 16-mm strip film and on magnetic tape. Trace, station, and date identification are printed on the film automatically at regular intervals. Precise time marks from a transistorized crystal-controlled timing system are placed on each record. The time is periodically



PLAT OF EXPERIMENTAL SEISMOLOGICAL STATION

FORT SILL, OKLAHOMA

FIG. 3. Array pattern.

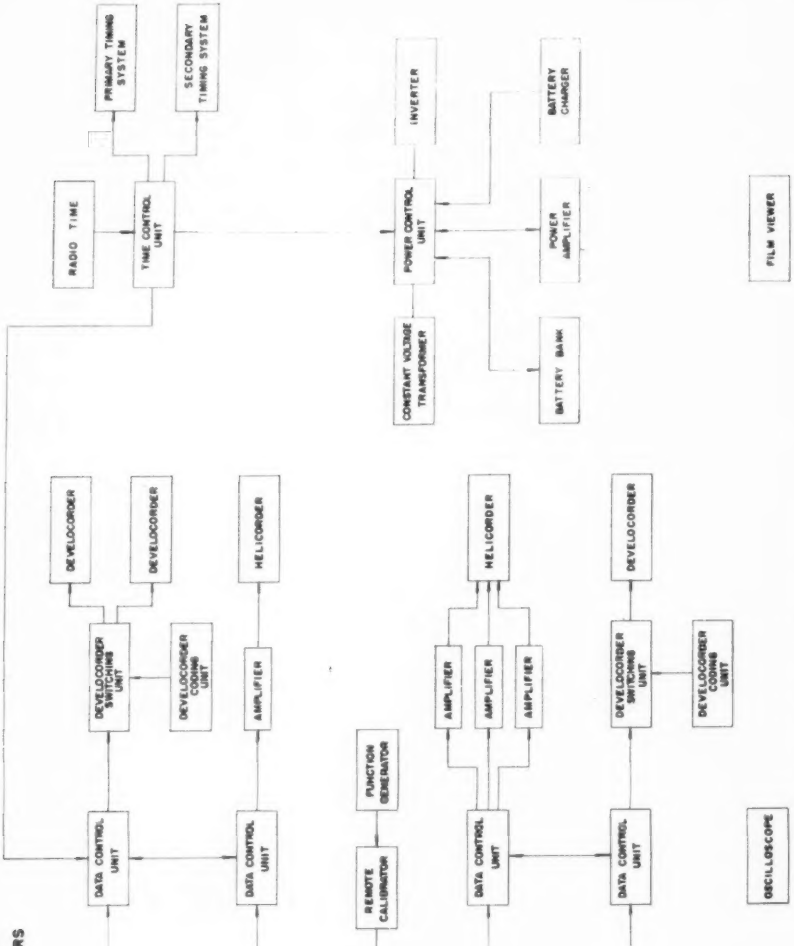


Fig. 4. Block diagram of instrumentation.

checked against radio time signals received from Radio Station WWV in Washington, D. C. A bank of nickel-cadmium batteries provides standby power in case the main power system fails.

INSTRUMENT RESPONSE CHARACTERISTICS

Figure 5 shows the response characteristics of the four different types of seismographs used at the observatory. The amplitude of earth vibration in the case of the curves shown is held constant. Magnification is defined as the ratio of deflection on the record to the deflection of the earth. The ten-element array and the three-component short-period seismographs are capable of very high magnification. They can be operated with the full magnification shown only in the quietest locations.

The response of the long-period seismographs is shown to the right in Figure 5. This type of response characteristic is best suited for the detection of long-period surface waves, whereas the response of the short-period seismograph is best suited for the detection of the shorter period body waves. The narrow-band seismograph emphasizes the period range of 1 to 3 seconds and rejects the shorter period signals. This type of response is very helpful in the study of shear waves. The magnification of the broad-band seismograph is limited by the 5- to 8-second microseismic noise always present in the earth; however, for larger disturbances it responds equally well to several wave types and provides a recording of the complete disturbance on a single trace. It should be noted that all four of the response characteristics have about the same magnification at a period of 6 to 7 seconds. This is because of the relatively high background noise in this period band. Experience has shown that the amplitude of the background noise decreases toward longer and shorter periods at about the same rate that the magnification increases on the short-period and the long-period seismographs.

The characteristics of the instrumentation which result in responses shown in Figure 5 are tabulated below. In each case the galvanometer is placed in a phototube amplifier rather than recording directly on photographic film or paper as is normally done in university observatories. This enables higher magnification and more flexibility in recording.

Instrument characteristics	*Short-period and array (SP)*	*Narrow-band (NB)*	*Broad-band (BB)*	*Long-period (LP)*
1. Seismometer free period (second)	1.0	2.5	12.5	25
2. Seismometer damping (% of critical)	1.0	0.065	0.4	1.0
3. Galvanometer free period (second)	0.2	0.64	0.64	30
4. Galvanometer damping (% of critical)	1.0	1.5	9.0	1.0
5. Filter bandpass at 3 db cutoff points (second)	0.1–100	0.05–100	0.05–100	25–1000
6. Filter cutoff rate at short-period side (db/octave)	12	12	12	12

VAULTS AND SEISMOMETERS

One of the small sealed vaults is shown in Figure 6. The earth normally used to cover the top of the vault is piled to the right. The data line terminations and lightning protection devices for the seismometer are mounted on the post shown in the right portion of the photograph.

Figure 7 is a photograph of the Benioff vertical seismometer, which is located in the small sealed vault shown in Figure 6. This instrument has an inertial mass of 100 kilograms; it uses a variable-reluctance type transducer and operates with a natural period of one second. When connected to its associated phototube amplifier, it will resolve earth motions as small as one angstrom unit (0.000,000,1 mm) at a frequency of one cps. This type of seismometer is used in seismological observatories throughout the world. It has a built-in calibration device so that calibrations can be performed without removing the cover from the vault.

Figure 8 is a view of the mound of earth that covers one of the large vaults. The vault is constructed of reinforced concrete and is located about 15 ft below the top of the mound. This is one of four vaults which house the long-period,

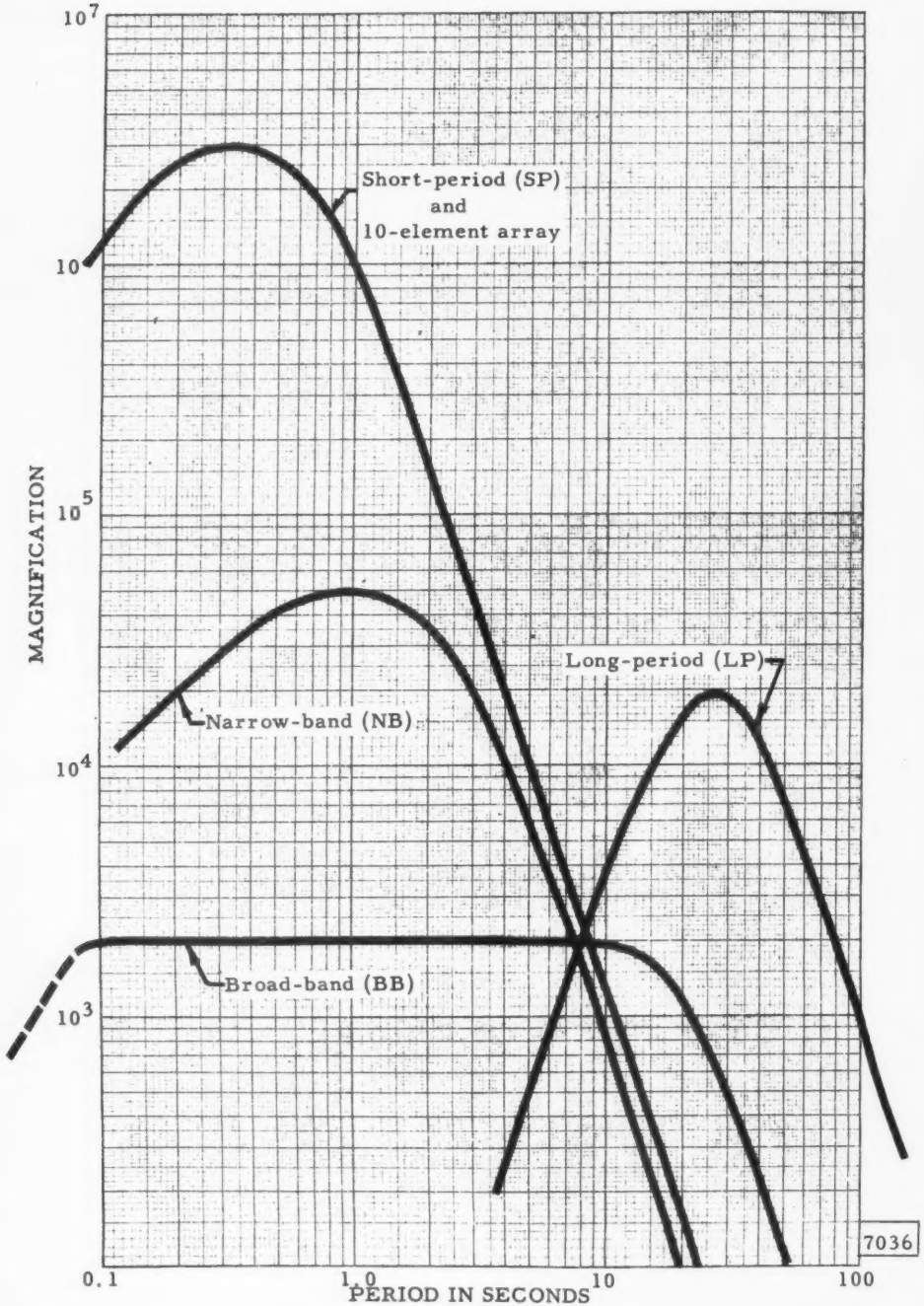


FIG. 5. Response characteristics of seismographs.

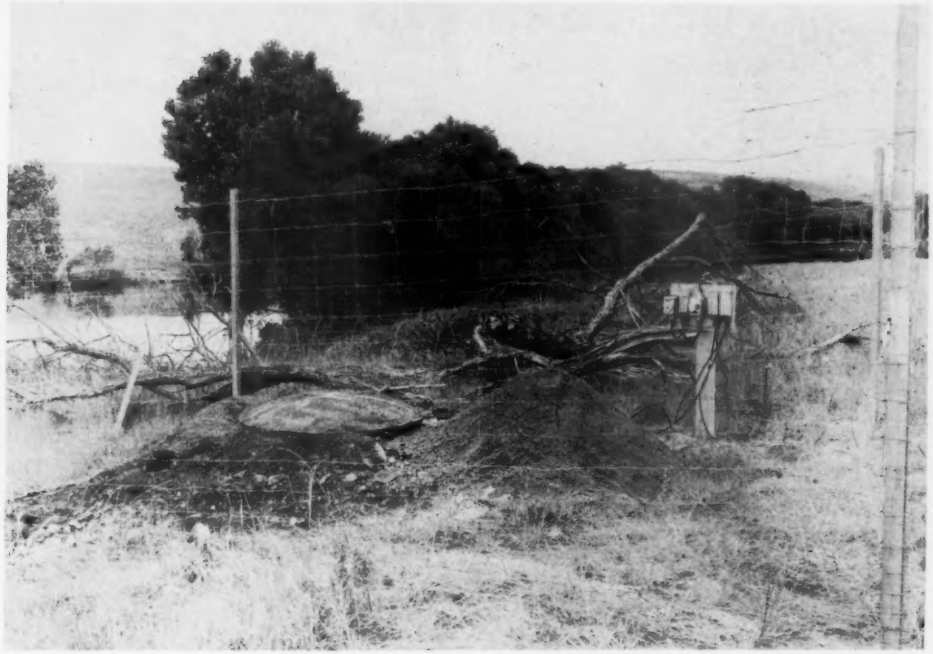


FIG. 6. New type sealed vault and signal line terminations. Earth covering is removed to expose top of vault.

short-period, narrow-band, and broad-band seismographs and four seismometers of the array. The seismometer used for the array and short-period seismograph was shown in Figure 7. The other seismometers are shown in Figures 9, 10, and 11, and described below.

a. Figure 9 shows the Sprengnether Vertical Seismometer which is used as the vertical component of the long-period seismograph. It has an inertial mass of about 7½ kilograms, a moving-coil type transducer, built-in calibrator, and is operated with a natural period of 25 seconds.

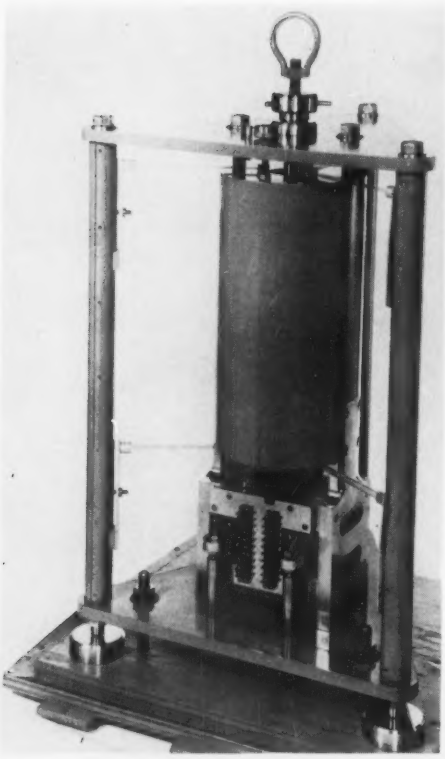
b. Figure 10 shows the Melton Vertical Seismometer which is used as the vertical component of the narrow-band seismograph. It has an inertial mass of about 5 kilograms, a moving-coil transducer and built-in calibrator, and is operated with a natural period of 2.5 seconds.

c. Figure 11 shows the Press-Ewing Vertical Seismometer which is used as the vertical component of the broad-band seismograph. It has an inertial mass of about 7½ kilograms, a moving-coil type transducer and built-in calibrator, and is operated with a natural period of 12½ seconds.

AMPLIFIERS

Figure 12 shows a view of the central-recording building and several supporting structures. The cables over which the electrical signals from the seismometers are transmitted are shown at the extreme left of the photograph. The cable enters the first building to the left which houses the phototube amplifiers. Here the signals are amplified and then routed to the line that carries the signal to the central-recording building shown on the right. The four small buildings in the center of the photograph are used for storage. The main power line can also be seen in the foreground.

Two types of amplifiers are located in the amplifier building. The short-period phototube amplifier is shown in Figure 13; the long-period photo tube amplifier is shown in Figure 14. In both cases the amplifiers are shown with their covers removed. The amplifiers are essentially the same except for the type and period of the galvanometer used to obtain the initial amplification. The light reflected from the galvanometer mirror falls on two photocells and the optical system is designed so that, as the galvanometer deflects, the



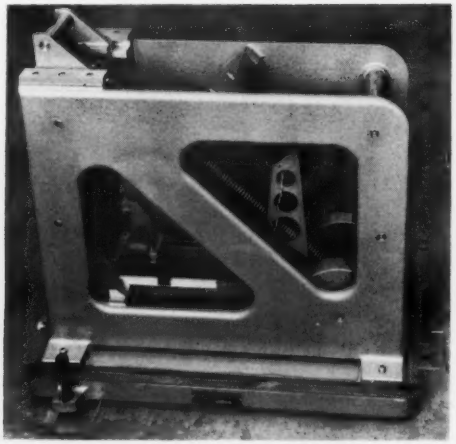


FIG. 9. Sprengnether vertical seismometer used in the long-period seismograph.

FIG. 7. Benioff vertical seismometer used in 10-element array and in 3-component short-period seismograph.

FIG. 8. Typical large underground vault, which contains four types of seismometers.

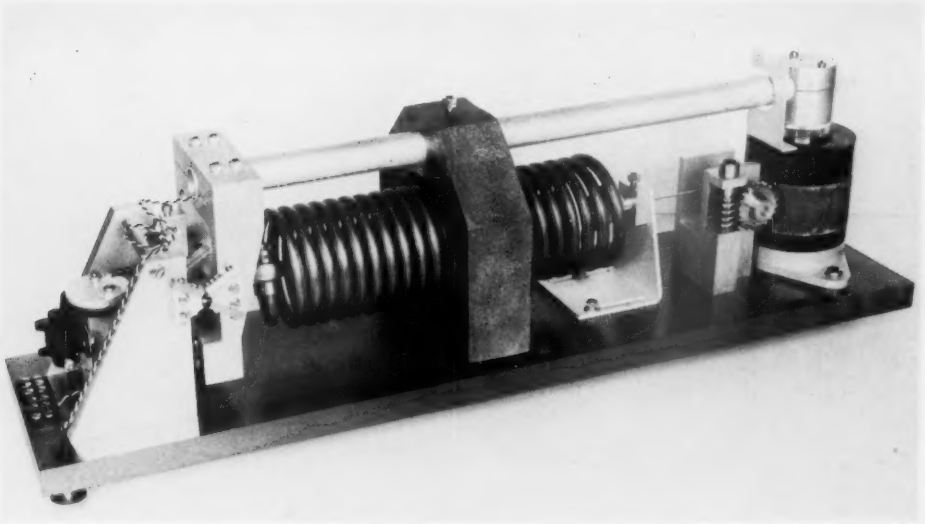


FIG. 10. Melton vertical seismometer used in the narrow-band seismograph.

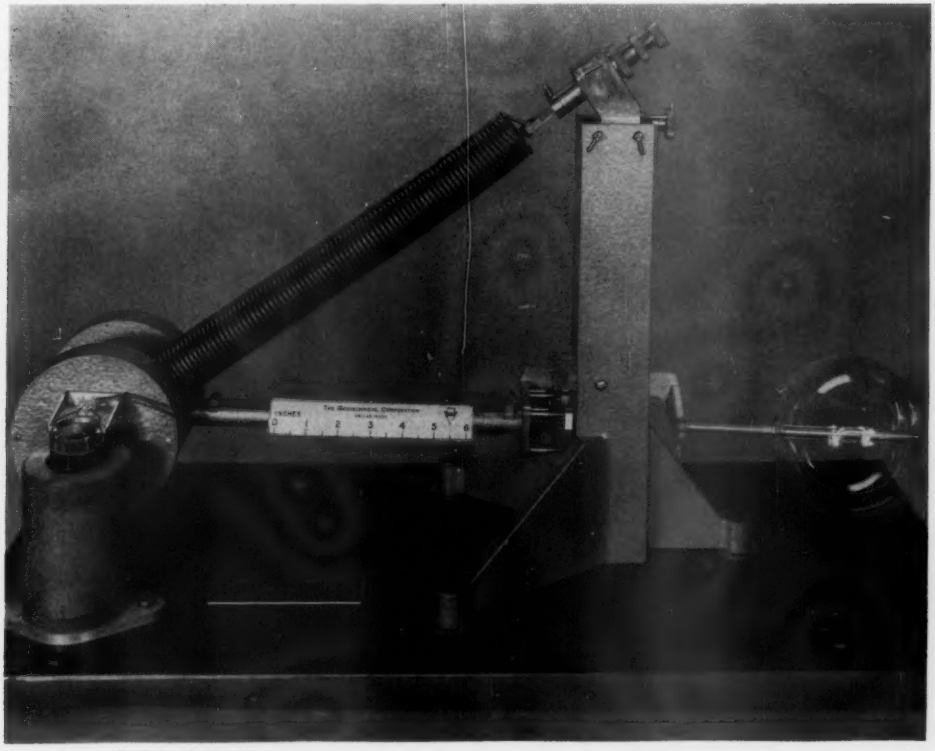


FIG. 11. Press-Ewing vertical seismometer used in the broad-band seismograph.

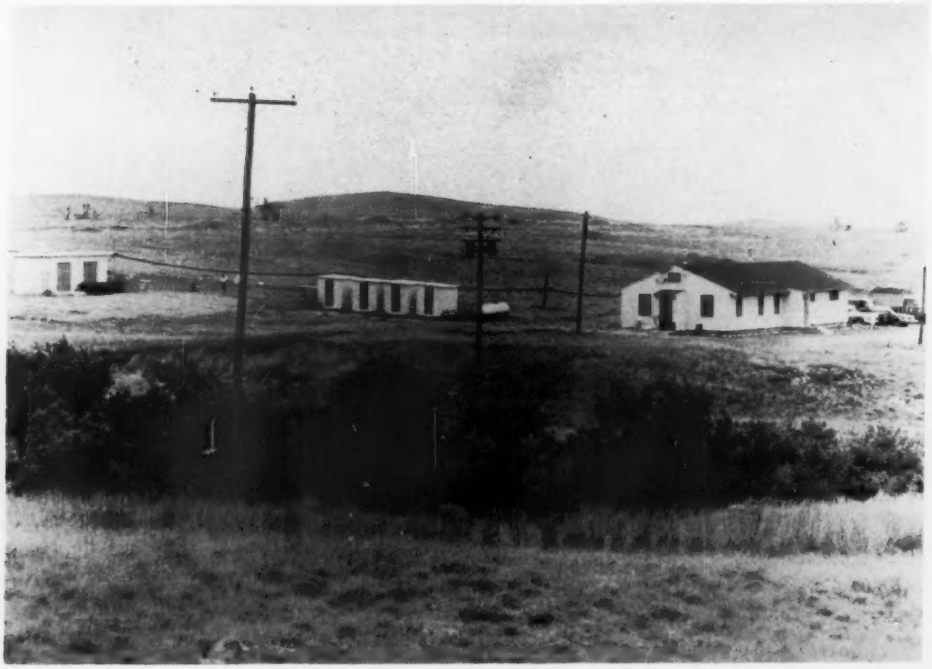


FIG. 12. From left to right are shown the amplifier building, four storage huts, and the central-recording building.

light varies in intensity but does not change its position on the photocells. This improves the linearity. Both amplifiers have an internal noise level low enough so that the thermal agitation noise of the seismometer coils can be seen. Two stages of cathode follower are used to match the impedance of the photocells to the lower impedance required to drive the recording devices. In each case, the galvanometer, phototubes, and other critical components are mounted in heavy metal cases that are sealed to prevent entry of moisture. Both amplifiers have a dynamic range of over 70 decibels and the short-period amplifier operates over a temperature range of from $-60°$ F. to $+120°$ F. The thermal stability of the amplifier using the long-period galvanometer is not as good because the long-period galvanometer is more sensitive to temperature changes. The use of the long-period galvanometer gives the added sensitivity and filtering required for the long-period seismograph.

DATA CONTROL, TIMING AND POWER

The amplified signals are transmitted over the data line from the amplifier building to the central-recording building where they are routed to the data control panels located in the right portion of the console shown in Figure 15. The nickel-cadmium batteries used for emergency operation when the main power fails are located in the cabinet on the left. The second cabinet from the left contains a radio receiver, radio time signal converter, crystal-controlled timing system, and power circuitry. The two center cabinets contain the monitor recorders on which signals from either the array or short-period, narrow-band, broad-band, or long-period seismometers can be recorded for monitoring or trouble-shooting. The recorder to the left has a single stylus and operates at a chart speed of 90 mm/minute. The recorder on the right has three styli and operates at a chart speed of 15 mm/minute. The data to be recorded are selected by patch cords shown on the two cabinets to the right of the recorders. The recorders are of the drum type using heat-sensitive paper. As the drum rotates, the stylus leads along the axis of the drum, subscribing a

helix similar to the way a lathe cuts a screw thread. After the recording is complete, the paper is removed from the recording drum, and when laid out flat, reads from left to right and top to bottom like the page from a book.

The two cabinets to the right of the monitor recorders contain the calibration equipment, data control modules, trace coding circuitry, oscilloscope, and accessory items. The data control modules are used to set the trace magnification levels and route the signals to the magnetic-tape and film recorders.

RECORDING

The magnetic-tape equipment is not shown in Figure 15 but is now located immediately to the right of the console. An Ampex FM magnetic-tape recorder is used and seven channels of data in the frequency range of from 0 to 20 cps are recorded. The tape speed is 0.3 inch per second, so

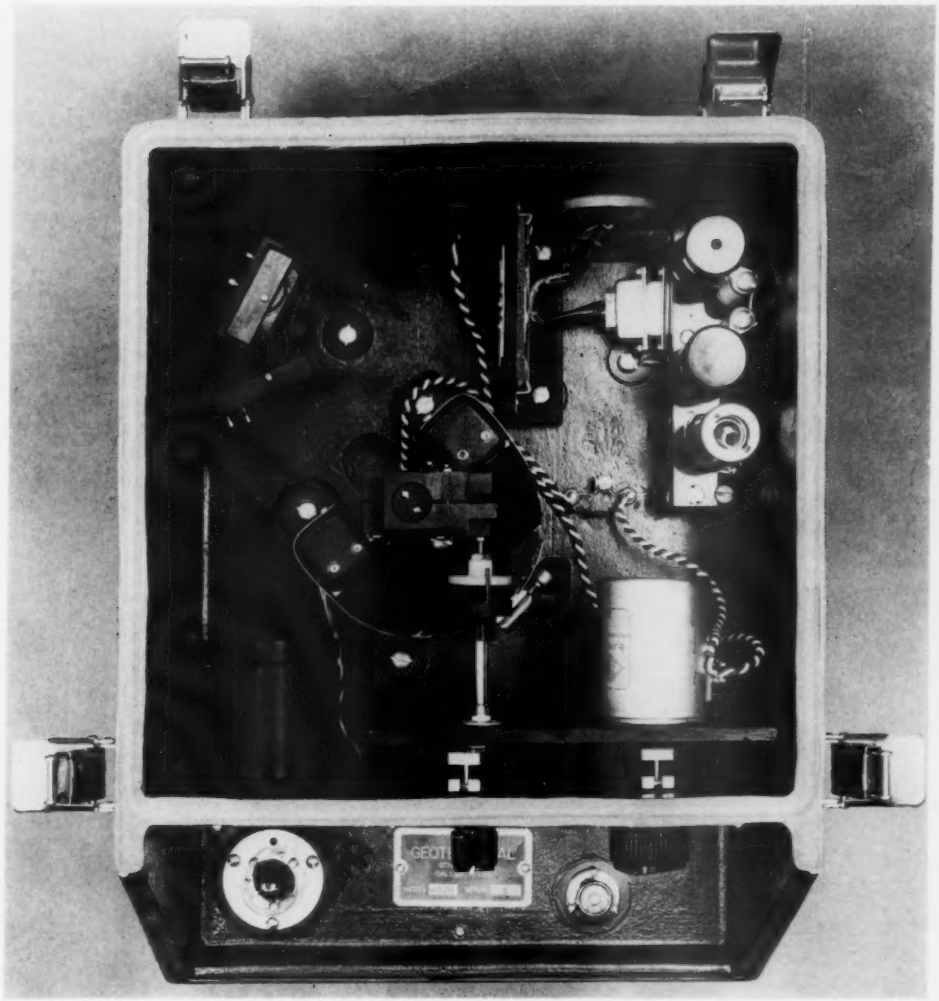


FIG. 13. Short-period phototube amplifier with cover removed.

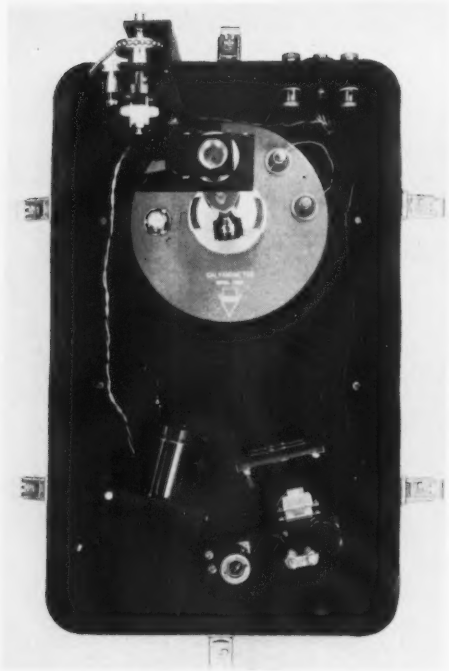


FIG. 14. Long-period phototube amplifier with cover removed.

a 2,500-ft roll of tape will record for 24 hours. It is hoped that a 14-track FM recorder and equipment to record several channels of data in digital form can be added to the observatory at a later date.

Figure 16 shows the film recorders which, in addition to the magnetic-tape recorder, are used for the primary recordings at the observatory. The recorders are located on the right in the photograph. Each recorder has 16 channels. The two recorders to the left record short-period and narrow-band information, including data from the array; the recorder at the right records long-period and broad-band data. Galvanometers with a natural frequency of 16 cps are used in all three recorders. The recordings are made on 16-mm film, which is processed automatically and projected on the viewscreen. In the short-period recorder, approximately ten minutes is required from the time the recording is made until the film is projected on the viewscreen. In the long-period recorder, approximately one hour is required.

Figure 17 shows a schematic of the automatic processing film recorder. The light reflected from the galvanometer mirrors is focused by an optical system onto an opal screen. The galvanometer light spots imaged on the opal screen are then recorded on the film at about $\times 10$ reduction by a standard 16-mm camera lens. The film is fed from the supply reel across the developer, fix, and wash rollers to the film take-up reel. A meniscus action is used to feed the liquids to the bottom surface of the film. The top part of the film is not wet during the developing process. Immediately after processing, the film is dried by a blower, then projected at $\times 10$ enlargement onto the viewing screen.

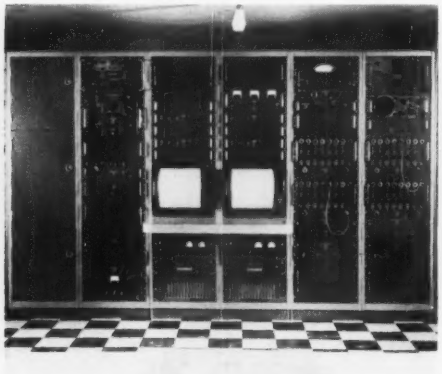


FIG. 15. Data control, time and power console in the central-recording building.

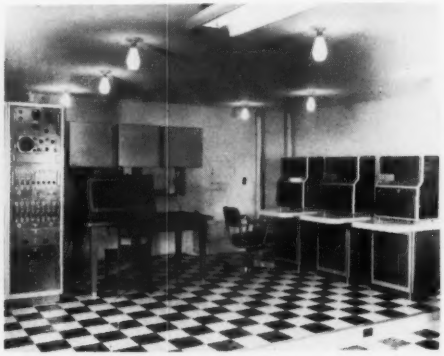


FIG. 16. From left to right are shown the data control console, film viewer, and film recorders in the central-recording building.

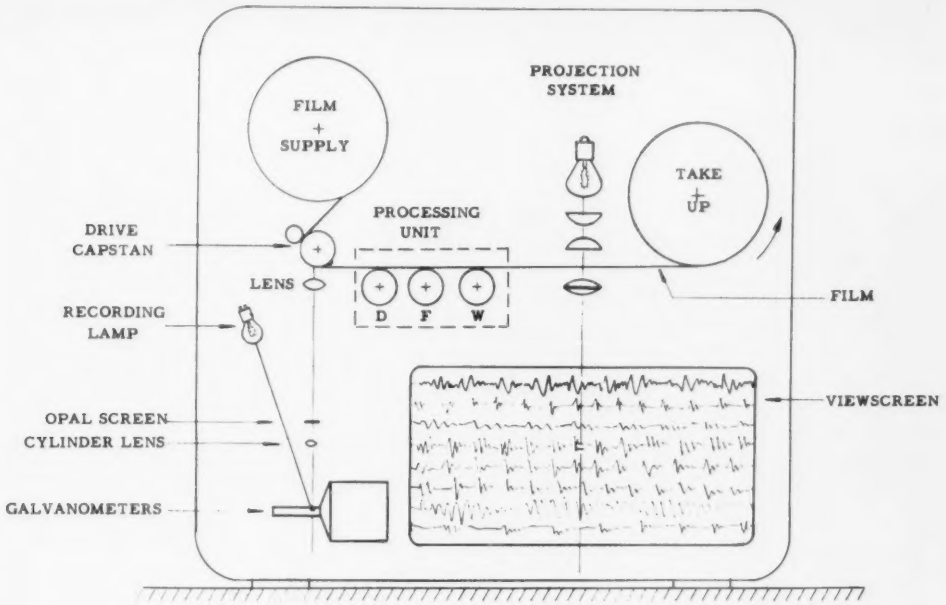


FIG. 17. Schematic of automatic processing recorder (Develocorder).

In short-period recording, approximately 150 ft of film per day are required and the film speed is 300 millimeters per minute as viewed on the recorder screen. In long-period recording, approximately 30 ft of film per day are required, and the film speed is 60 millimeters per minute as viewed on the screen of the recorder.

SEISMOGRAMS

Figure 18 shows three samples of the type of recording made on the 16-mm film. The uppermost film is a recording of a long-period vertical seismometer, a 1/10 magnification trace of the long-period seismometer, a narrow-band vertical seismometer, and a broad-band vertical seismometer. The signal shown is a train of surface waves from an earthquake. The numerals shown represent Greenwich time and are printed automatically on the film each minute. Each five minutes a station identification letter and numerals indicating the day and year are printed on the film. The center film is that of several short-period Benioff vertical seismometers and the recording is of a quarry blast located about 20 km from the seismometers. The numerals representing Greenwich time are spaced at one-minute intervals and the difference in film speed can be seen by comparing the spacing between successive time numerals on the upper and lower films. The lower film is a recording of a multi-seismometer array in which the uppermost traces are the summation of several combinations of seismometers and the lower traces are single seismometers. The microseisms with a period of about six seconds are not cancelled by the array and can be clearly seen on the upper traces of the lower film sample.

Figure 19 shows the viewer that is used to view these films; the viewer is also shown in Figure 16. The film reels are placed on top of the viewer and a rapid film transport mechanism allows any point on a 150-ft roll of film to be located in about 30 seconds. A variable-speed slow transport is provided for scanning the film. Magnification is $\times 20$. The time scale on the screen is 10 mm/sec for the short-period recordings and two mm/sec for the long-period recordings.

By using this type of film-recording equipment, data from several seismometers can be recorded side by side and directly compared as to signal-to-noise ratio, phase shift, and amplitude re-

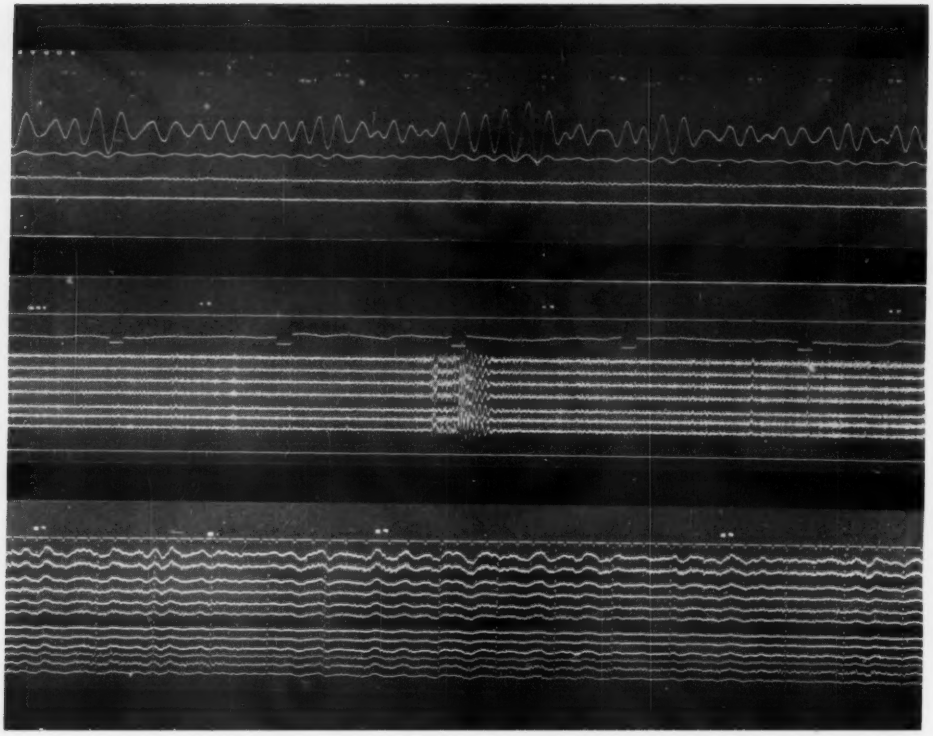


FIG. 18. Enlargement of section of 16-mm film records (approximately ×3).

sponse. For selected events, more detailed comparison will be made by analysis of magnetic-tape recordings; however, it is thought that much preliminary work can be done from the film records and that magnetic-tape records will be used only for detailed analysis of selected events.

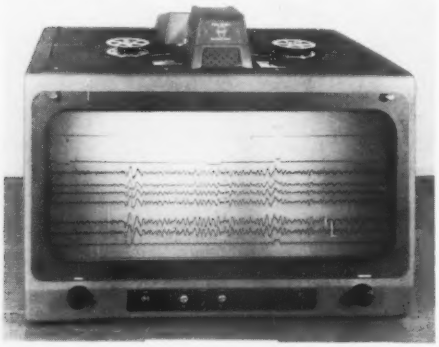


FIG. 19. Viewer for use in analysis of 16-mm film records. Screen is 28 inches long by 12 inches high. Magnification is ×20.

CONCLUSIONS

The Wichita Mountains Seismological Observatory is well equipped and is located at a site with a low background noise. Other instrumentation characteristics can be obtained by using different plug-in filters in the phototube amplifiers and by changing the natural period and coupling of the seismometers and galvanometers. Continuous spectrum analysis of noise and signals and detailed analysis of significant seismic events recorded on magnetic tape should prove very informative. The station is located at a convenient distance from Californian and Mexican earthquakes and should provide a significant contribution to the science of detecting and identifying underground nuclear explosions and earthquakes.

APPENDIX I

Excerpt from page 16 of the *Report of the Conference of Experts to Study the Methods of Detecting Violations of a Possible Agreement on the Suspension of Nuclear Tests*

A. *Seismic apparatus*

The seismic apparatus of the control post should include:

(1) Approximately 10 short-period vertical seismographs dispersed over a distance of 1.5–3 km and connected to the recording system by lines of cable. The seismographs should have a maximum magnification of the order of 10^6 at a frequency of 1 cps and a receiving band adequate to reproduce the characteristic form of the seismic signal;

(2) 2 horizontal seismographs with the parameters indicated in point (1);

(3) One three-component installation of long-period seismographs having a broad receiving band and a constant magnification of the order of $10^3-2\times10^3$ in the period range 1–10 seconds;

(4) One three-component installation of seismographs with a narrow receiving band and magnification of the order of 3×10^4 when $T=2$–2.5 seconds;

(5) At certain posts one three-component installation of long-period seismographs with magnification of the order of $10^4-2\times10^4$ at period of $T=25$ seconds;

(6) Auxiliary equipment necessary in order to get precise records of the seismic signal; recording devices, chronometers, power supply units and apparatus for receiving automatic radio-signals giving correct time.

The seismic apparatus should be installed in places with a minimal level of micro-seismic background, away from industrial areas, and on outcrops of bedrock (where possible). The seismographs should be installed in suitable vaults.

The area required for installing the seismic apparatus should be about 3×3 km.

GEOPHYSICS, VOL. XXVI, NO. 3 (JUNE, 1961), PP. 374–393, 17 FIGS.

SPACE EXPLORATION, A CONTINUING EFFORT*

ALLEN J. McMAHON†

Abstract: Space exploration is carried on for political, scientific, military, economic, and psychological reasons. Today, sound, practical reasons exist to continue and extend the use of satellites to improve methods of meterology, communications and navigation; to name only a few. Scientific discoveries accruing from sound, well-planned space exploration, and their influence on American industries, can only dimly be forseen. Further exploration effort promises to increase and emphasize the role played by the sun in a wide variety of human activities. The satellite Explorer VI and the space probe Pioneer V have extended communications to ranges of 20,000,000 miles; have increased scientific-knowledge of the properties of the exosphere with respect to magnetic fields and energetic charged particles.

The space between the planets, far from being empty, is repeatedly being disturbed by great clouds of ionized gas called plasma. These are examples of the unusual and intriguing problems awaiting space exploration. Solution of these and unknown problems can best be achieved by continuous and diligent effort. The part played by the United States in space exploration has been excellent to date. The long range pay-off of such superb effort can scarcely fail to enrich this country, initially, militarily and eventually economically.

INTRODUCTION

The proposed program of the United States for space exploration is not small, and since it will become increasingly expensive, it is appropriate to examine the reasons for undertaking a thorough, integrated, and continuing effort. A program possessing continuity and yet the flexibility to exploit unanticipated discoveries appears to be the minimum acceptable; lacking continuity and flexibility, great waste may occur, and opportunities for scientific advances may be wasted.

The reasons for space exploration may be listed in four categories: psychological-political, economic, scientific and military. For security reasons, military programs are not discussed here.

PSYCHOLOGICAL-POLITICAL REASONS FOR EXPLORATION

The psychological-political reasons for space exploration appear to some people to be the overwhelming ones for supporting space research. For example, the Soviet government has chosen to time its projects for maximum political propaganda advantage. In the opinion of George V. Allen, Director of the United States Information Agency, Soviet science has recently been beneficiary of a significant change in world opinion. The Russian propaganda apparatus has courted and exploited this change; Soviet writers have presented the propaganda image of Russian preeminence in nontechnical fields by virtue of their space successes. However, it is wrong and dangerous to discount the importance and the impact of the Russian achievements. In the struggle for prestige, the Russians have proved that, when they choose to do so, they can master difficult and advanced technologies and are not limited to imitation. Briefly, these are some of the political considerations which exert an influence on the plans and programs for space exploration. Yet is is almost certainly true that politics cannot of itself be the basis for a sound, constructive program.

Another aspect of space exploration depends on its psychological value; space exploration, insofar as it answers the aspiration of people to know nature and to contemplate ideas of great magnitude, enlists these sound reasons for its support. Scientific research, for example, is fueled by such reasons.

ECONOMIC APPLICATIONS

Space exploration has had practical application in the fields of economy, science, and the mili-

* Presented at the 30th Annual International Meeting of the Society of Exploration Geophysicists, November 1960, Galveston, Texas.

† Space Technology Laboratories, Inc., Los Angeles 45, California.

tary. As examples of economic applications of space research, three technologies should be mentioned; these are the utilization of satellites for communication, meteorological prediction, and for navigation.

Communications Techniques

Techniques utilizing reflecting surfaces of orbiting objects for point-to-point communications are the simplest example of a practical space accomplishment. Best publicized is the Echo satellite program. Exhibiting naked eye visibility, the first of these satellites was injected into an orbit with an apogee of 1,051 miles and a perigee of 943 miles, on August 12, 1960. Total weight of the 100-ft plastic sphere is 135 pounds, and it was fabricated of milar film 0.0005 inch thick. Communications were established between Goldstone, California, and Holmdel, New Jersey, at 2,390 megacycles using 10 kilowatts of radiated power from the 85-ft Goldstone antenna on August 12. Subsequent to the initial contact, many communications experiments have been performed, using the Echo satellite, by government and private groups.

The American Telephone and Telegraph Company wishes to establish a network of possibly 50 Echo type satellites to create additional telephone and television channels, Holmes (1960). Such techniques appear inexpensive, reliable and attractive to military and commercial users. Simple reflecting techniques will soon be supplemented by active systems which intercept, amplify, redirect and relay messages from one place to another. Cost wise, eventually satellites should be able to provide the means to large scale telecasts less expensively than microwave links such as are presently utilized in the United States.

Navigation Applications

On April 13, 1960, the first navigation satellite, Transit 1B, was launched, Freitag (1960). Developed under contract to the United States Navy, this system promises to have far reaching implications for the shipping industry and commercial aviation. It is expected that its data will be made available to the general public.

Although Transit has practical, economic implications, this system also is of military value. Transit is a Doppler navigation system under development by the Johns Hopkins University, Applied Physics Laboratory. Figure 1 is a schematic of the system operation in which Doppler shift is proportional to the radial velocity between the navigating vehicle and the satellite. The accuracy of the fixes obtained by this system is degraded by the refraction of the ionosphere and by the nonspherical shape of the earth. The correction for refraction is achieved by transmission on each of two frequencies. Thus, a measure of refraction can be made and compensated for. The oblateness of the earth must be independently determined and corrected for in tracking.

At a given observation point on the earth only one trajectory of the satellite can be correlated with a given curve of Doppler shift. Thus, the position of the observer relative to the satellite may then be determined and the position of the observer on the earth computed. Several navigation experiments have been completed with Transit 1B; a fix of a point in Austin, Texas, was made which agreed with the first order survey position to an accuracy of 0.25 mile. Fixes with accuracies of 0.1 mile appear to be possible.

Meteorological Applications

Discussion of the meteorological results obtainable from a satellite should be prefaced with a word of caution. At present, understanding of terrestrial weather is based on measurements made within the atmosphere. A satellite will provide cloud cover information and heat flow data for uninhabited and oceanic areas not presently observed; this information initially will supplement, not supplant, ground weather observations. The hope is that satellite data descriptive of the earth as a heat engine, i.e., intensity of radiant energy received from the sun and radiated into space, and descriptive of the formation and evolution of storms, will lead to a new and better understanding of weather.

Specifically, the solar constant is believed to vary by no more than 0.3 percent. Occasionally, solar plasma clouds are estimated to augment by 10 percent energy intercepted by the earth. Variations of absorbed energy also depend on cloud and snow cover. Data upon these conditions and upon the infrared radiation emitted by the earth may be obtained by a satellite.

Preliminary measurements of the earth and its atmosphere were made by Explorer VII, launched in October 1959. This satellite, carrying six sensors for weather data acquisition, obtained the first meaningful measurements of the earth's

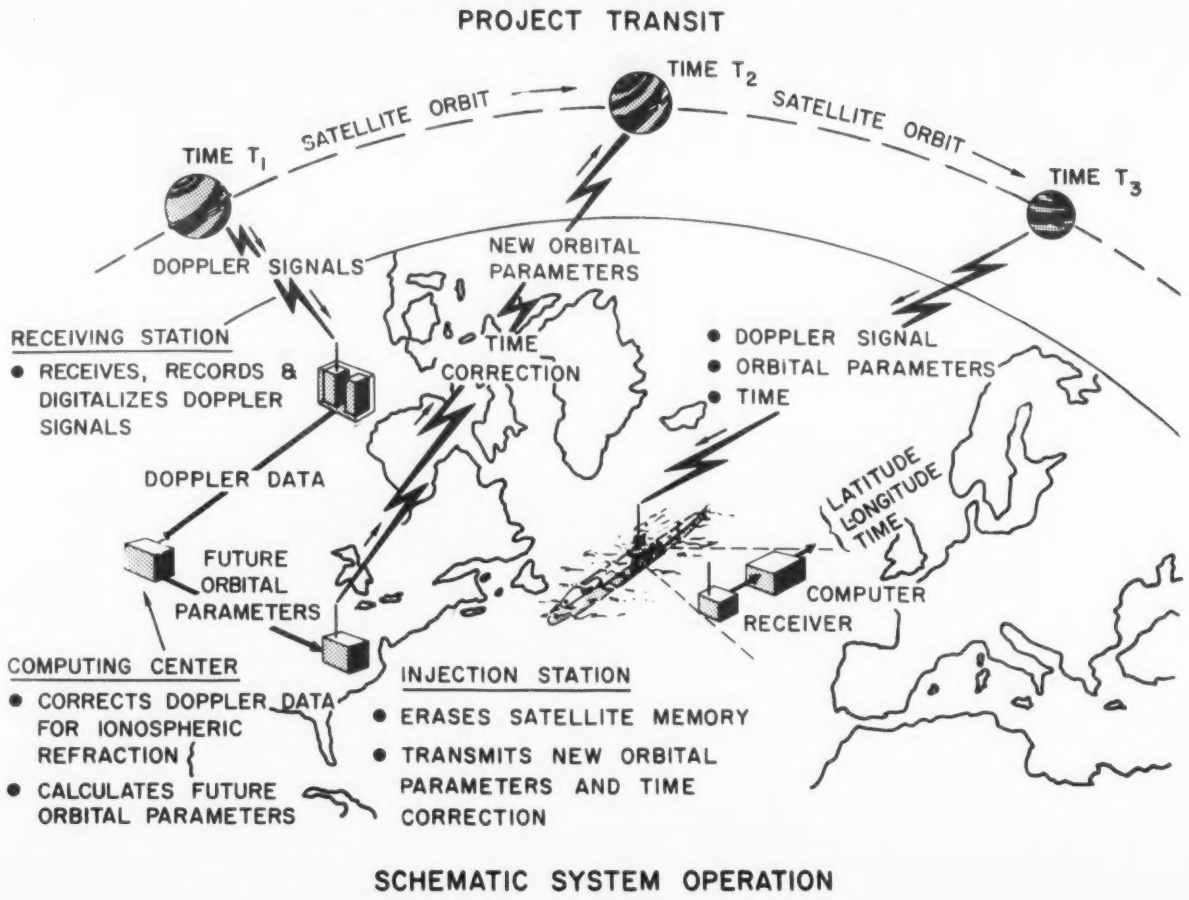


FIG. 1. Transit system operation.

radiation budget. The first meteorological satellite was Tiros I, launched April 1, 1960. The following pictures are cloud cover images of the earth which were obtained by Tiros I. Figure 2 is a cyclonic storm occurring on April 1 at 11:55 EST. A surface weather map is shown for approximately the same time. The Gulf of St. Lawrence is the dark area in the upper right section. Figure 3 shows a tropical storm over the central Pacific Ocean; wide and narrow television cameras are shown on the left and right side of the figure. Figure 4 is a typhoon in the Pacific Ocean. Tiros I recorded an approximate total of 23,000 cloud photographs, 60 percent of good quality, Holmes (1960). An area containing cumulonimbus clouds was identified by Tiros I on May 19, 1960. This region later became the spawning ground of a line of tornadoes and hailstorms striking Oklahoma and Texas. Such data and special supplementary cloud maps proved to be of great value. Data from Tiros II, which is scheduled for late 1960 orbit, will be widely distributed as the weather forecast system is called on to provide information vital to aviation, shipping, agriculture, and many consumer industries. Such investigations promise to increase accuracy of forecasts and to extend prediction times; the economic effect may be great indeed.

SCIENTIFIC RESEARCH THROUGH MID-1960

Programs undertaken and completed by the United States have been surprisingly effective and productive of discoveries. It is safe to say that the Soviet Union surpassed us at first, certainly in the size of their booster motors; but it is also true that American space science has been superior and compensates to some extent for our late start in vehicle development.

The problem appears to be, "Will we prepare a vigorous, continuing, and basic science program which establishes the foundation for sound research and attracts the energies and enthusiasms of theorists as well as experimentalists." To some, it is too early to expect that an equal burden of effort can be accepted by theory and experiment. I hope and believe that this opinion is not accepted. Each payload must be carefully planned well in advance, incorporating checks of such theoretical physics as appear feasible.

Payloads will soon evolve into a phase where several aspects including the theoretical foundation, the mission, instrumentation, telemetry, etc., will be integrated and optimized to investigate a limited number of problems of space science. Another payload of the same species, possessing different instrumentation, will fulfill a different specialized mission. Thus, particular launches will implement specific scientific research problems. The intent to achieve such specialization can be recognized in the NASA observatory series of satellites, OGO, OSO, and OAO.

A summary of the space explorations undertaken to date by the United States and the Soviet Union is shown in Table 1, Herrick (1960). To typify the excellent quality of the American space research, a discussion of the results obtained from the Explorer VI satellite and the Pioneer V space probe is given below. It should be emphasized that extremely valuable results were obtained from Explorers I, III, IV and VII, from the Vanguards, and from the Pioneers I, III, and IV. The Explorer I and III data exhibited puzzling phenomena until McIlwain of the Iowa group recognized in them the characteristics of Geiger counter saturation, implying very high counting rates. Van Allen and his collaborators then predicted an intense zone of radiation surrounding the earth, which prediction was fully vindicated in later launches, both American and Russian.

Explorer VI and Pioneer V: Scientific Results

The two projects discussed were carried out by Space Technology Laboratories, Inc., under the direction of the Air Force Ballistic Missile Division for the National Aeronautics and Space Administration.

Explorer VI

Explorer VI, see Figure 5, was launched into a highly elliptical earth orbit on August 7, 1959. The scientific results obtained from the flight of this satellite are reported in the "Project Able-3 Final Mission Report, Volume 2," Space Technology Laboratories, Inc., (August 1960). This satellite was injected into an orbit with an apogee of 22,926 nautical miles and perigee of 136 nautical miles. It was equipped with a variety of charged particle detectors which were operated continuously. Included were (1) a scintillation counter, (2) a proportional counter telescope, and (3) a Geiger counter and Neher ionization chamber.

Electromagnetic wave propagation experiments

(*Continued on page 381*)

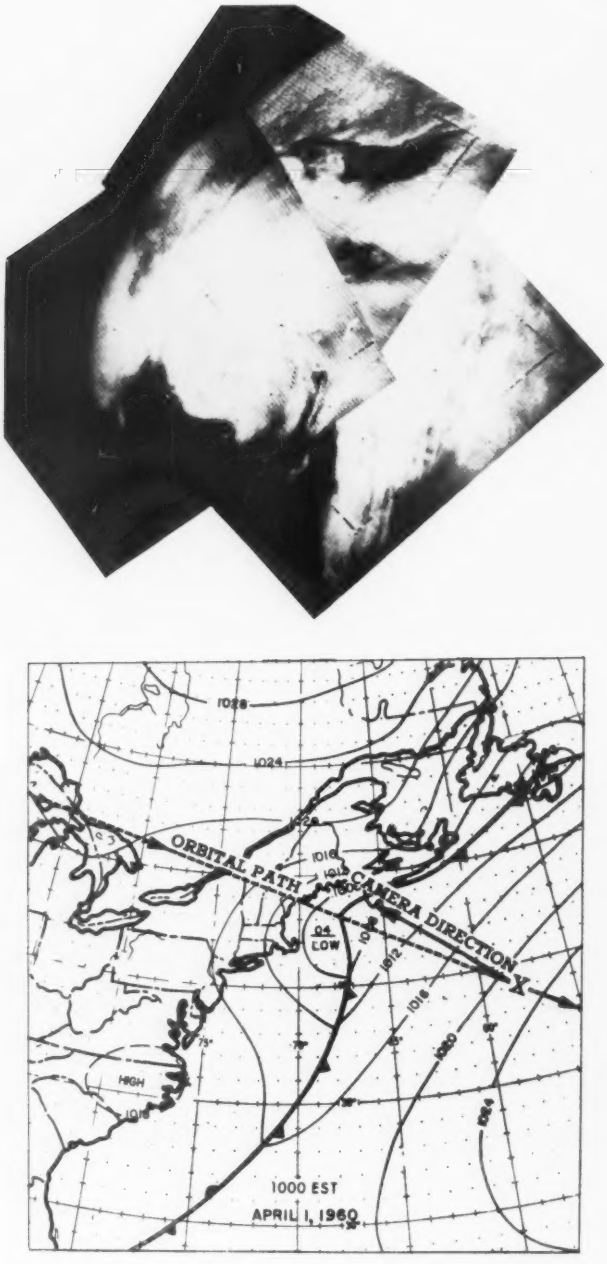


FIG. 2. Storm off the East Coast, from Tiros I.

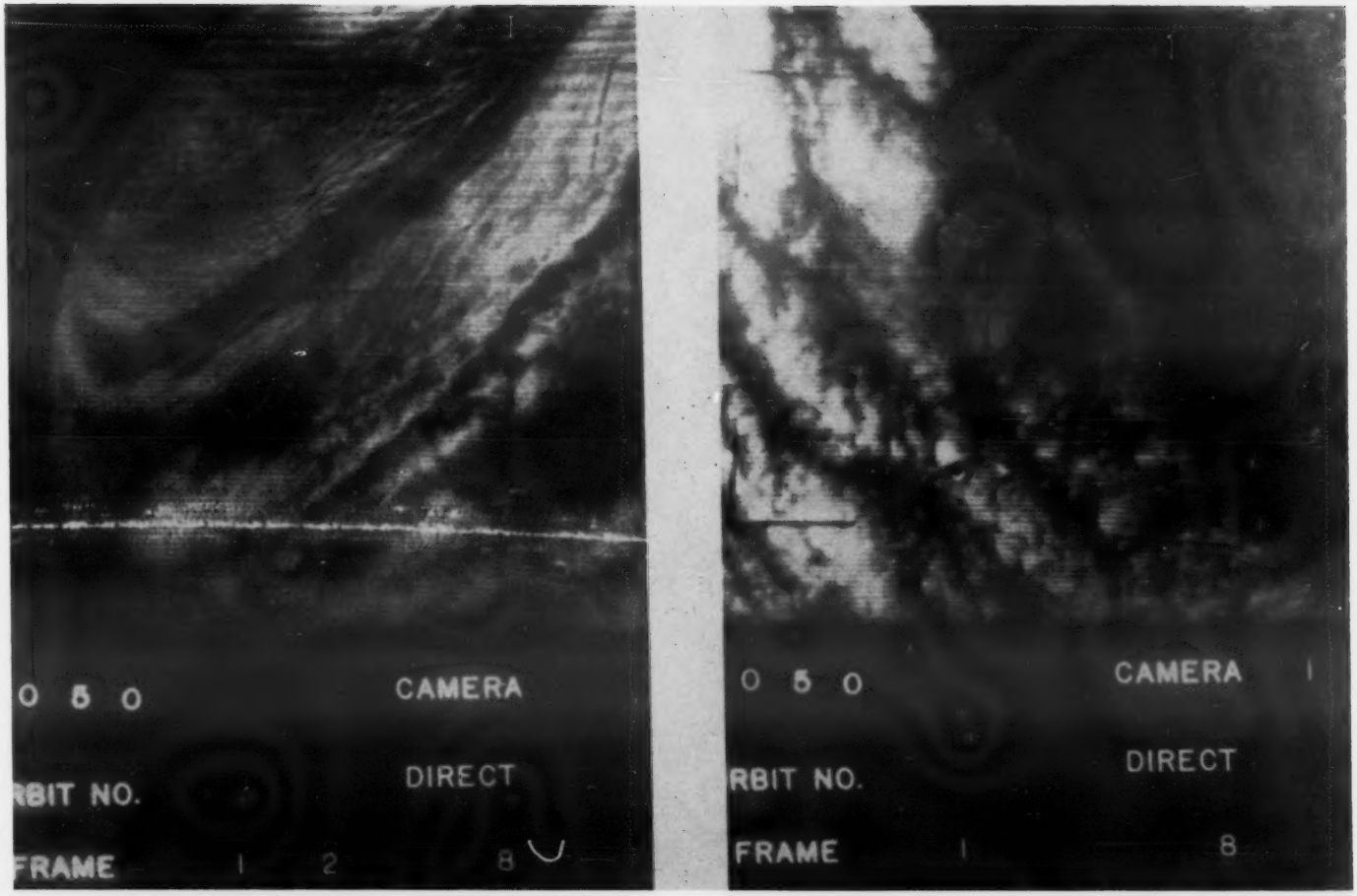


FIG. 3. Tropical storm in the Pacific, wide and narrow angle views.

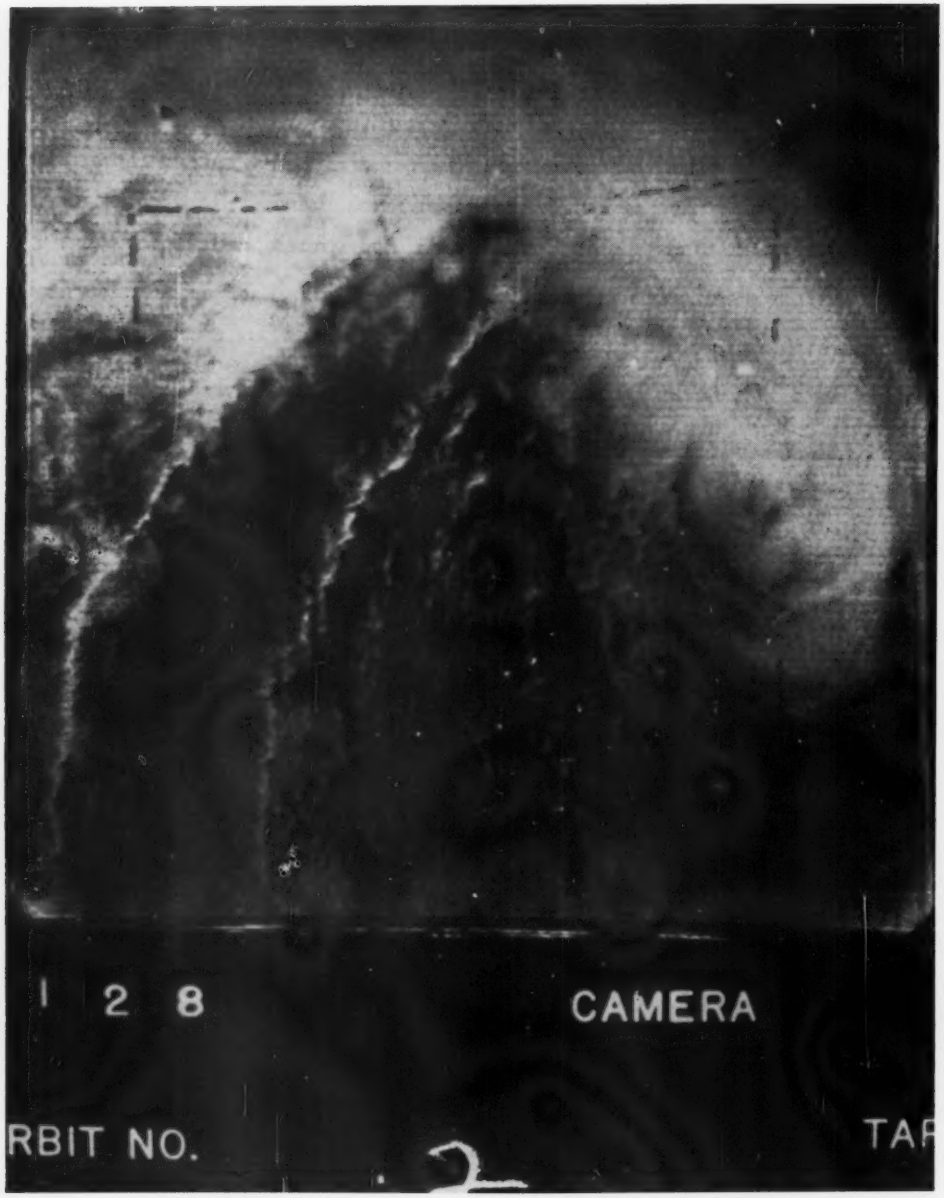


FIG. 4. Cyclonic storm in the Pacific Ocean area.

Table 1. Space Explorations

Vehicle	Launch Date	Status	Type	Perigee (miles)	Apogee (miles)	Period (minutes)
		1957				
Sputnik I	4 Oct	Down 4 Jan 1958	Earth Sat	142	588	96.17[1]
Sputnik II	3 Nov	Down 14 Apr 1958	Earth Sat	140	1,038	103.7[1]
		1958				
Explorer I	31 Jan	In orbit 3–5 yrs	Earth Sat	217	1,185	107.7[2]
Vanguard I	17 Mar	In orbit 200–2000 yrs	Earth Sat	406	2,447	133.8[2]
Explorer III	26 Mar	Down 28 Jun 1958	Earth Sat	121	1,746	115.87[2]
Sputnik III	15 May	Down 6 Apr 1960	Earth Sat	105	238	89.7[1]
Explorer IV	26 Jul	Down Oct 1958	Earth Sat	163	1,380	110.27[2]
Pioneer I	11 Oct	Down 12 Oct 1958	Lunar Probe	alt: 70,700 miles		
Pioneer III	6 Dec	Down 7 Dec 1958	Lunar Probe	alt: 63,580 miles		
Project Score	18 Dec	Down 21 Jan 1959	Earth Sat	110	920	101.46[2]
		1959				
Lunik I (Mechta)	2 Jan	In orbit millions of yrs	Space Probe	In solar orbit—15 month period		
Vanguard II	17 Feb	In orbit 100 yrs	Earth Sat	347	2,046	125.3[3]
Discoverer I	28 Feb	Down 5 Mar 1959	Earth Sat	99	605	95.9[2]
Pioneer IV	3 Mar	In orbit millions of yrs	Space Probe	In solar orbit—406.95 day period		
Discoverer II	13 Apr	Down 26 Apr 1959	Earth Sat	142	220	90.5[2]
Explorer VI	7 Aug	In orbit more than 1 yr, unknown status	Earth Sat	115	24,618	753.6[4]
Discoverer V	13 Aug	Down 28 Sept 1959	Earth Sat	136	450	94[2]
Discoverer VI	19 Aug	Down 20 Oct 1959	Earth Sat	138	537	95.28[2]
Lunik II	12 Sept	Impact on Moon	Lunar Probe	Total flight time appr 35 hrs		
Vanguard III	18 Sept	In orbit 30–40 yrs	Earth Sat	320	2,320	129.5[3]
Lunik III	4 Oct	Down 20 Apr 1960	Earth Sat	24,840	292,000	15 days
Explorer VII	13 Oct	In orbit 20–30 yrs	Earth Sat	344	672	101.2[3]
Discoverer VII	7 Nov	Down 26 Nov 1959	Earth Sat	104	550	95[2]
Discoverer VIII	20 Nov	Down 8 Mar 1960	Earth Sat	120	1,056	103.7[2]
		1960				
Pioneer V	11 Mar	In orbit millions of yrs	Space Probe	311.64 days orbit around sun		
Tiros I	1 Apr	In orbit	Earth Sat	429	468	99.2[3]
Transit 1B	13 Apr	In orbit	Earth Sat	238	439	95.5[3]
Discoverer XI	15 Apr	Down 26 Apr 1960	Earth Sat	109	380	92.35[2]
Sputnik IV	15 May	In orbit	Earth Sat	175	400	93.8[1]
Midas II	24 May	In orbit	Earth Sat	300	318	94.4[3]
Transit 2A	22 Jun	In orbit 50 yrs	Earth Sat	389	650	101.7[3]
Discoverer XIII	10 Aug	In orbit	Earth Sat	153	375	93.1[4]
Echo I	12 Aug	In orbit	Earth Sat	900	1,091	118.2[3]
Discoverer XIV	18 Aug	Down 25 Sept 1960	Earth Sat	116	502	94.5[2]
Sputnik V	19 Aug	Down 20 Aug 1960	Earth Sat	189	210	90.72[1]
Courier 1B	4 Oct	In orbit	Earth Sat	502	658	106.71[5]

[1] Russian press released figures.
[2] Initial orbit.
[3] As of July 5, 1960.
[4] As of April 12, 1960, present position uncertain.
[5] As of Oct 13, 1960.

were carried out utilizing the telemetry radiations and a special VLF receiving system. Information on exospheric electron density was obtained from measurements made on the telemetry signals. The VLF system was designed to obtain data pertinent to atmospheric whistlers.

Studies of the magnetic field of the earth were made with a search coil magnetometer and a flux gate magnetometer. A spot television scanning system was provided and a low resolution image of the earth was achieved. A micrometeorite experiment was provided to obtain statistics on the momentum flux of micrometeorites in the exosphere.

During the flight of Explorer VI, a solar flare occurring on August 14, 1959 was observed photographically on the surface of the sun. Figure 6 (Giovanelli) shows an image of this flare near peak intensity. Such a flare represents the release of approximately 10^{30} ergs of energy. This is as much energy as is released by about 10,000 earthquakes of an 8.5 Richter scale intensity.

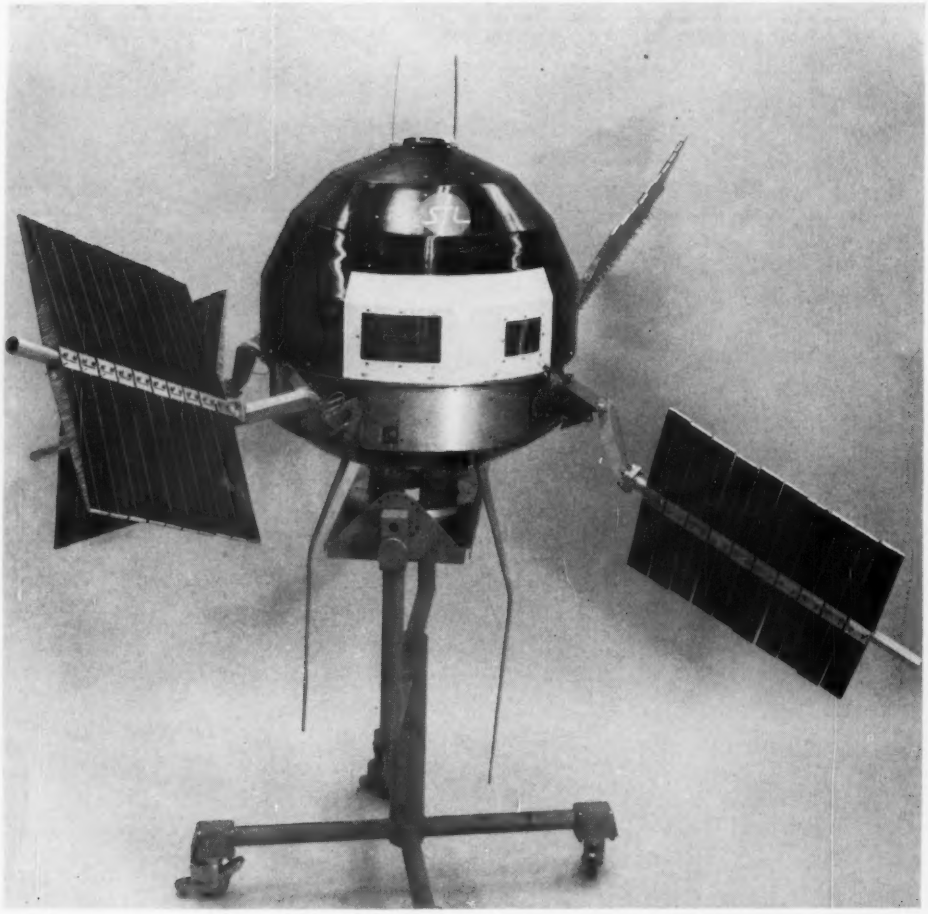


FIG. 5. Explorer VI prior to launch.

Shown below are curves demonstrating the effects of clouds of plasma which were associated with this flare. It can be computed that these particles travelled the 93,000,000 miles from the sun to the earth in about 52 hours, at velocities believed to approach 800 km/sec. Intense perturbations were caused in the Van Allen radiation zones by this flare.

It is appropriate here to illustrate the Van Allen radiation zones. Figure 7 diagrams the earth on the left; extending above its surface in toroidal symmetry are two zones of charged particles, believed to be primarily protons and electrons. Present evidence indicates that these large clouds configure into two zones which are probably formed by two independent injection processes. The data shown here were derived from measurements made by the Explorer VI scintillation counter. This counter observed less distinction between the inner and outer zones than did the Geiger counter experiments such as those used by Van Allen. The inner mushroom shaped region represents an instrument counting rate exceeding 5×10^5 counts/second. The bands as one scans to the right represent 5×10^5 counts/second, 10^5, 10^4, and 10^3 counts/second. All points with the same number designation were obtained on a given orbital pass. A graphic example of changes produced in the Van Allen radiation zone by the arrival of the plasma parti-

cles associated with the flare of 0040 GMT, August 14, 1959 is seen in Figure 8. It appears that initial effects of arrival of flare particles was a "dumping" into earth's atmosphere of some of the trapped radiation zone particles. Later, the particle intensity increased again.

Space contains significant structure in the form of charged particle zones. Explorer VI and Pioneer V obtained evidence for a third structural feature observed in nearby space. This evidence was obtained by the magnetometer experiments included in Explorer VI and was sustained by data from Pioneer V. The third structure is called an extraterrestrial current system or ring current. Figure 9 displays sample magnetometer data observed on August 9, 1959. Shown are the theoretical total field dependence for a dipole field (short dashes) and the theoretical perpendicular field for a dipole plus a toroidal equatorial current at about ten earth radii (solid line).

The data may be fitted to a theoretical expression for the terrestrial field which includes the effect of a current of 5×10^6 amperes at 60,000 km altitude, with a cross-section of about 18,000 km or less. Figure 10 is a diagram of this current system as seen by Pioneer V and Explorer VI. This structure is exterior to the outer Van Allen zone.

A further example of Explorer VI results is illustrated in Figure 11, which shows magnetometer and scintillation counter data from August 9, 1959. This comparison is evidence for the operation of a betatron mechanism for acceleration of particles in the radiation zones. It is illustrative of the results obtainable from two or more experiments in a single payload. Payloads must be

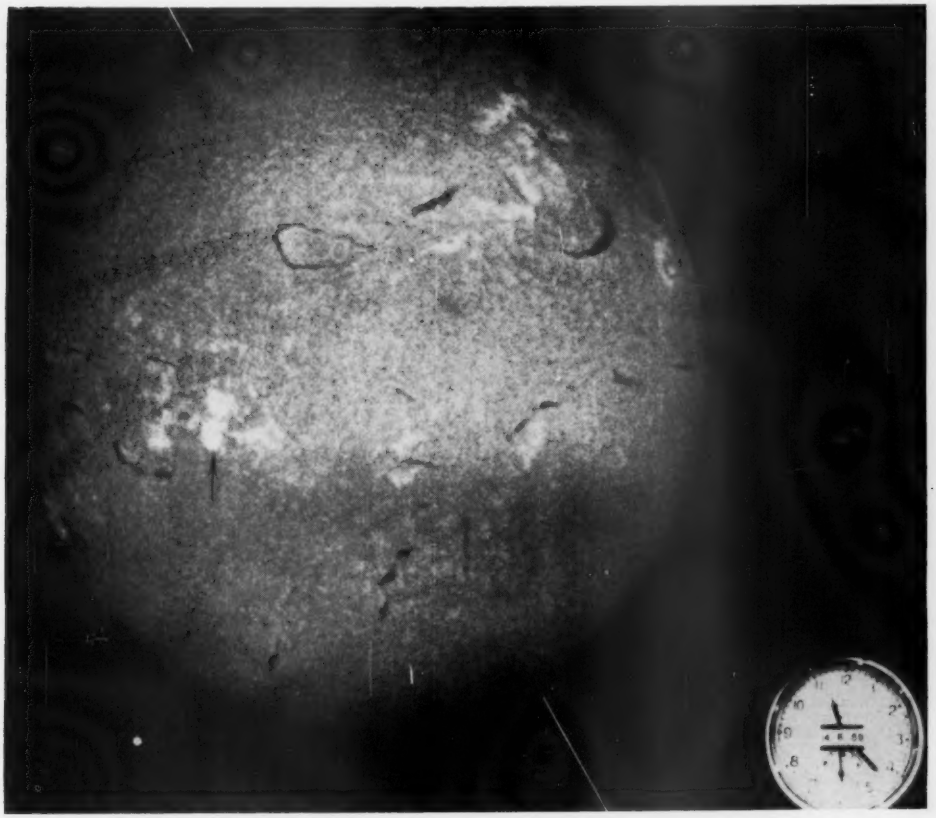


FIG. 6. Intense solar flare of August 14, 1959. Flare associated phenomena were observed at Explorer VI. White dot represents the earth to scale. (Courtesy of R. G. Giovanelli, CSIRO, Australia)

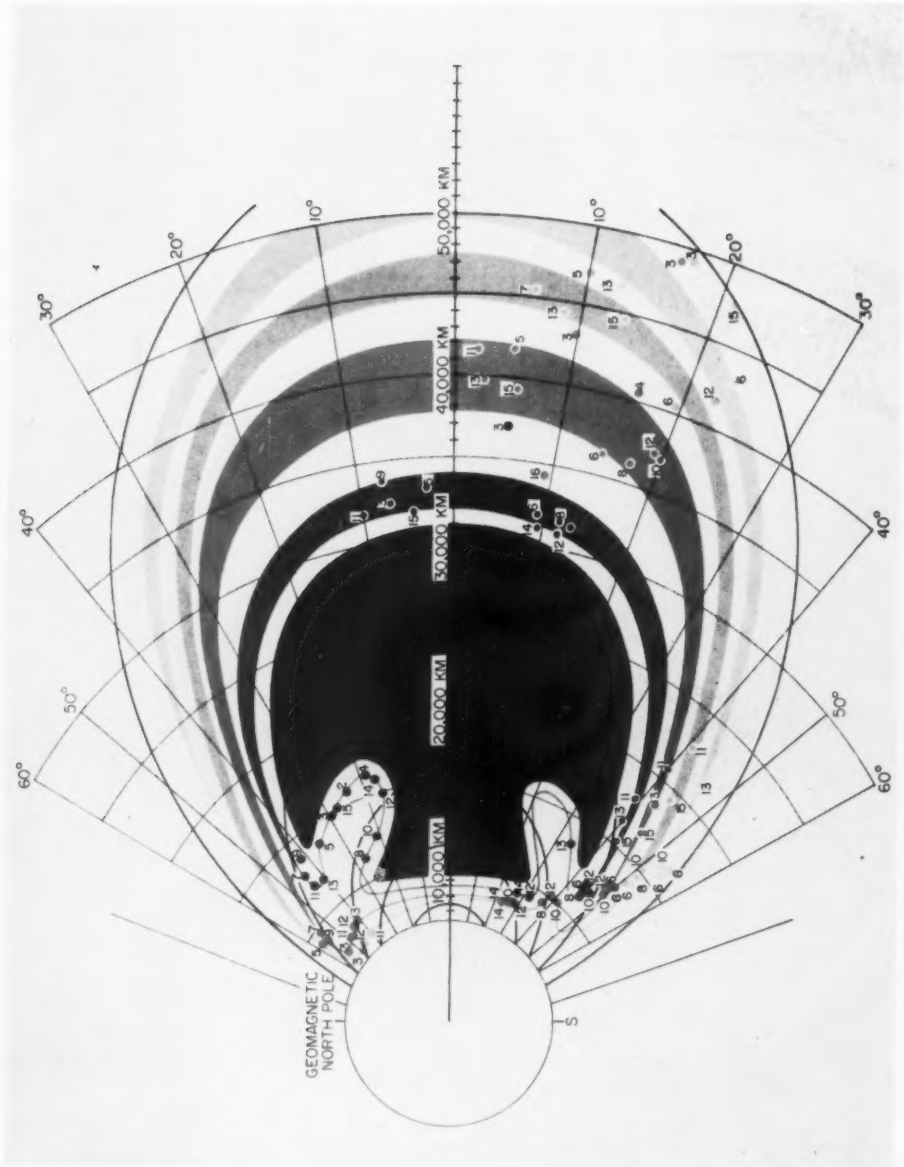


FIG. 7. Isointensity contours of the radiation zones as observed by a scintillation counter on Explorer VI.

planned to maximize the probability of obtaining complementary data such as this from several instruments.

Finally, Figure 12 shows the data which indicate that solar cosmic rays are produced and are accelerated by some process associated with a solar flare. These data, showing only a factor of two increase in cosmic ray background, indicate a new lower limit for the quantity of accelerated cosmic ray protons associated with flares. The effect in the ionosphere was too small to be observed. These data also define an upper limit to magnitude of randomly oriented interplanetary field since these particles, undeviated by random magnetic field, arrived promptly at Explorer VI.

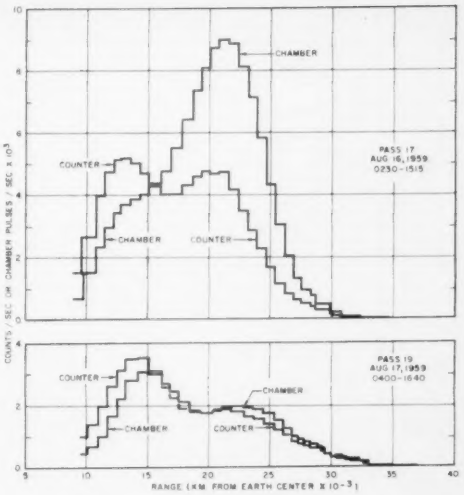
Pioneer V Results

Pioneer V, launched on March 11, 1960, epitomizes American space exploration; not only did it produce significant scientific data, but also it continued to transmit until June 26, 1960 when 22,462,000 miles from the earth.

The flight occurred during a period of intense solar activity. To illustrate the solar flare effects observed at this payload and at the earth, consider Figure 13, Greenstadt & Moreton (1960). It is clear from this figure that the strongest flares and registration of magnetic activity on Pioneer V are related. The velocities which may be computed for the flares of March 14, and 27 and for April 22 and 25 range from 870 to 1,680 km/sec in their transit from the sun. The center histogram is the index of magnetic activity at the earth's surface. Many, not all, of the flares are correlated with the earth's magnetic activity. Also shown in Figure 13 is the deviation in telemetry signal strength; it appears not to be correlated with flares.

In 1938, Scott E. Forbush reported decreases in cosmic ray background counting rate of several percent, occasionally lasting several days. On March 31, 1960 at 0800 UT, a severe magnetic storm began at the earth; a large Forbush decrease, as observed by the geiger counter, occurred simultaneously on Pioneer V (Arnoldy, Hoffman, Winckler).

Forbush decreases had been explained by disturbances in the earth's magnetic field causing a change in the minimum energy a particle must possess to penetrate to the surface. These magnetic field changes were presumed to be caused



Comparison of a Pass at the Beginning of the Geomagnetic Storm and a Pass 24 Hours Later.

FIG. 8. The effect on the Van Allen zones of the arrival of solar flare particles.

by plasma from the sun distorting the terrestrial magnetic field. This explanation appears untenable since this decrease was observed at Pioneer V 5,000,000 km from the earth and its field. Figure 14 shows the 28 percent Forbush decrease of April 1, 1960 observed at Pioneer V at this distance from Earth.

Figure 14 is remarkable since phenomena associated with two flares, occurring 2 days apart, can be seen. Direct detection by the Pioneer V cosmic ray telescope of particles accelerated by a process associated with the second solar flare was observed in these data (see Figure 14); evidently solar flare associated particles causing ionization in the earth's atmosphere cannot have been stored in the earth's magnetic field in the instance of April 1 flare.

NASA PROGRAMS FOR FUTURE EXPLORATION

A discussion of space exploration programs throws perspective on the accomplishments of the past and is evidence of the vigor and soundness of the effort that the United States has proposed to undertake.

United States efforts to explore the moon, probe interplanetary space, and voyage to nearby planets are the administrative responsibility of the National Aeronautics and Space Administra-

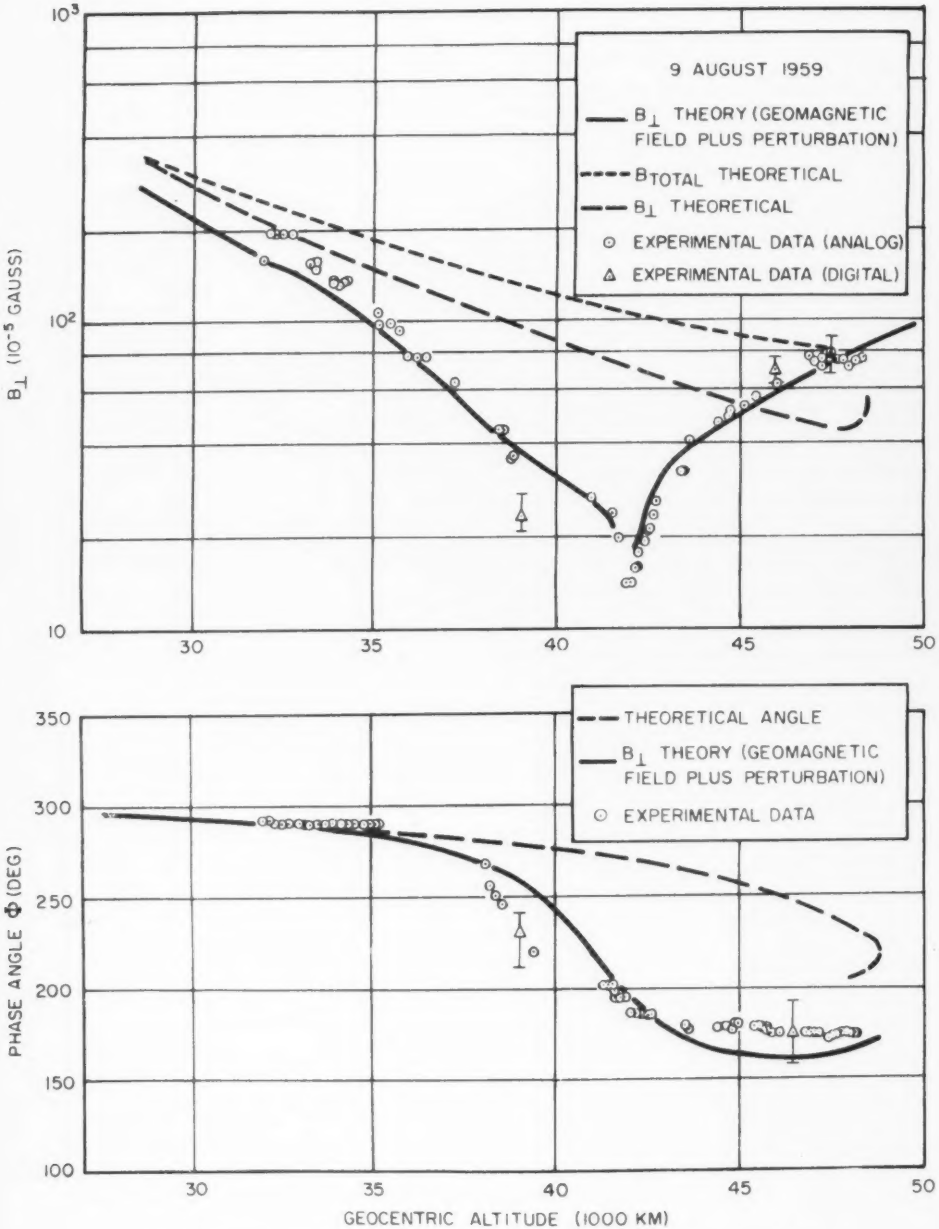


FIG. 9. Magnetic field measurements believed to be evidence of an extraterrestrial current system. Data from August 9, 1959.

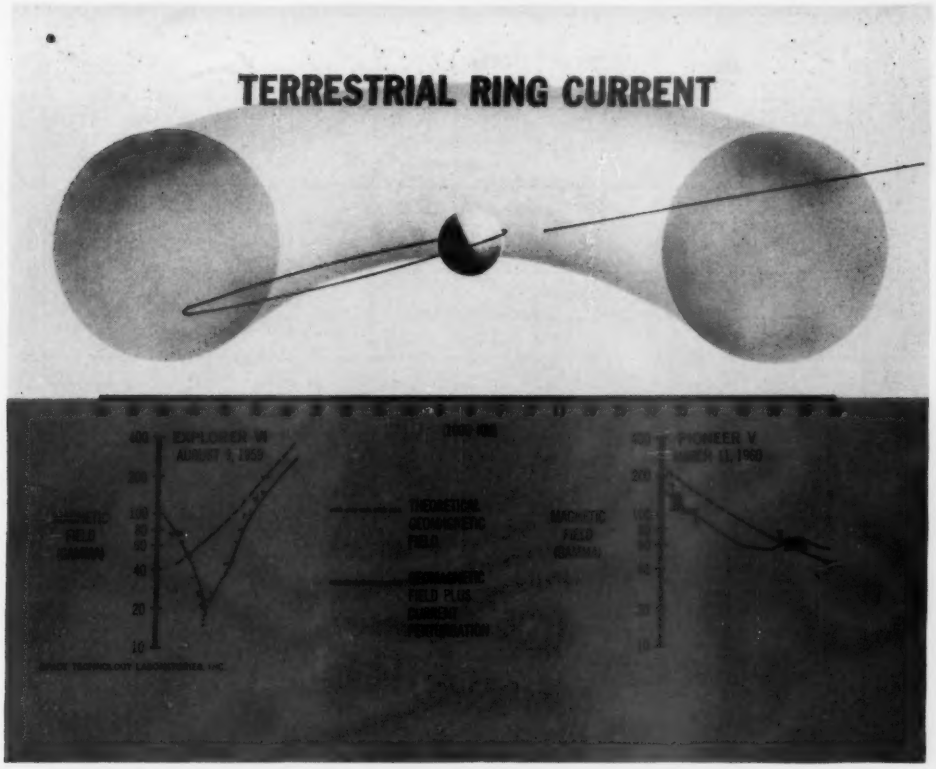


FIG. 10. Ring current model.

tion. NASA, aware of the need to marshal the best talent available for space exploration, has scheduled conferences to familiarize industry and the scientific community with its programs and needs. The information given here has been abstracted from NASA hearings in Congress (1960), and from the transcript of the first of these conferences. The record of the fourth conference, scheduled for October 26, is worthy of study.[1]

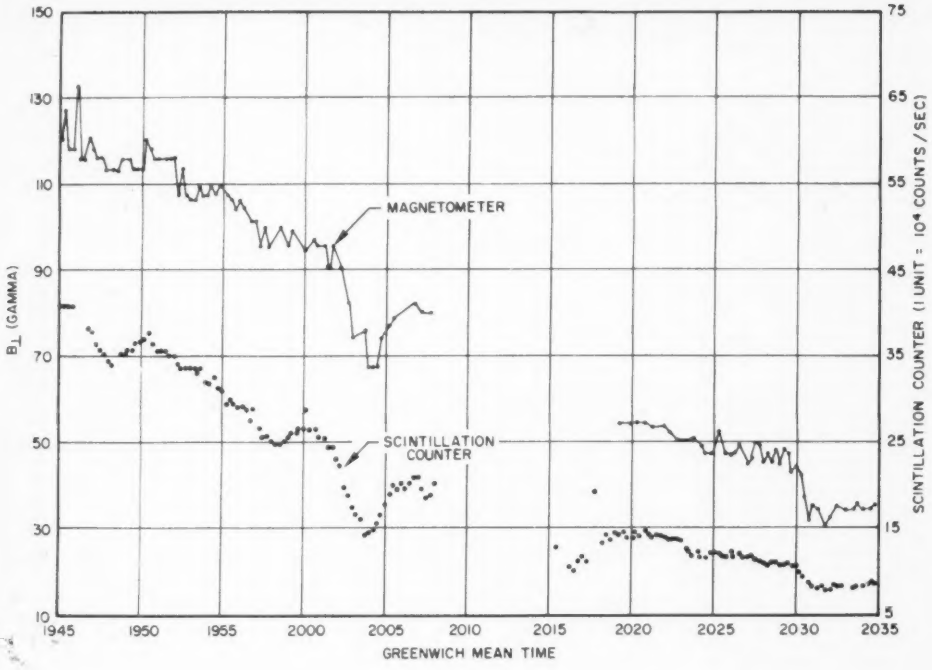
NASA conducts atmospheric flight research, manned space efforts, materials and structures research, and directs a world-wide tracking system. It conducts research on propulsion and secondary power generation, directs applications of space exploration, and conducts activities required for peaceful exploration of space. This paper will discuss the last three categories. NASA has a budget of $915 million for fiscal 1961; its 10-year plan calls for an effort of $12 to $15 billion through 1970.

[1] Not available before publication.

Vehicle Development

By far the largest part of the NASA budget has been devoted to development of vehicles and large booster motors necessary for future spacecraft as prospects for significant space exploration depend on reliable, large propulsive motors and vehicles. In fact, soft landings on extra-terrestrial surfaces await the development of the Centaur and Saturn vehicles. As an indication of the size of boosters needed, payload weights for various missions are listed in Table 2.

Manned landing on the moon and return can be achieved by three techniques: (1) brute force such as Nova, (2) refueling from earth orbit, e.g., using Saturn, (3) or development of nuclear upper stages for Saturn. It is not clear, for lunar landings, which system is optimum. For a Mars



Nonstorm In-phase Correlations.

FIG. 11. Correlation between the magnetometer and the scintillation counter aboard Explorer VI.

orbit and return, initiated from an earth-orbiting 150,000 pound satellite, a chemically propelled return payload would weigh 3,000 pounds, a nuclear propelled one 20,000 pounds, and an electrically propelled payload 30,000 pounds. For this mission, chemical propulsion is probably not competitive.

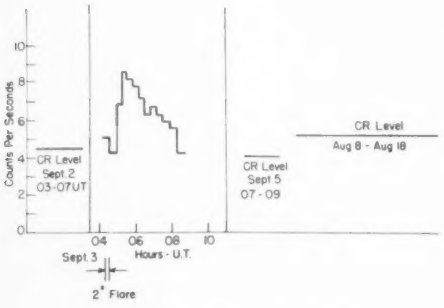


FIG. 12. Small cosmic ray increase associated with a solar flare.

Spacecraft Plans

Nomenclature, mission, and launch dates of space exploration payloads are listed in Table 3.

Orbiting Observatories

Among the geophysical satellites are the orbiting observatories, including the OAO, the Orbiting Astronomical Observatory; OGO, the Orbiting Geophysical Observatory; and OSO, the Orbiting Solar Observatory. The largest, weighing about 3,500 pounds, is the astronomical observatory. Figure 15 shows a NASA interpretation of the external configuration of the OAO. Several satellites of this configuration will be launched, the first in late 1963. This satellite will enable scientists for the first time to view the universe without peering through the filter which is the atmosphere. At the earths' surface, only visible light and a range of radio frequencies are relatively undiminished by absorption bands in the atmosphere, yet the sun and stars are known to

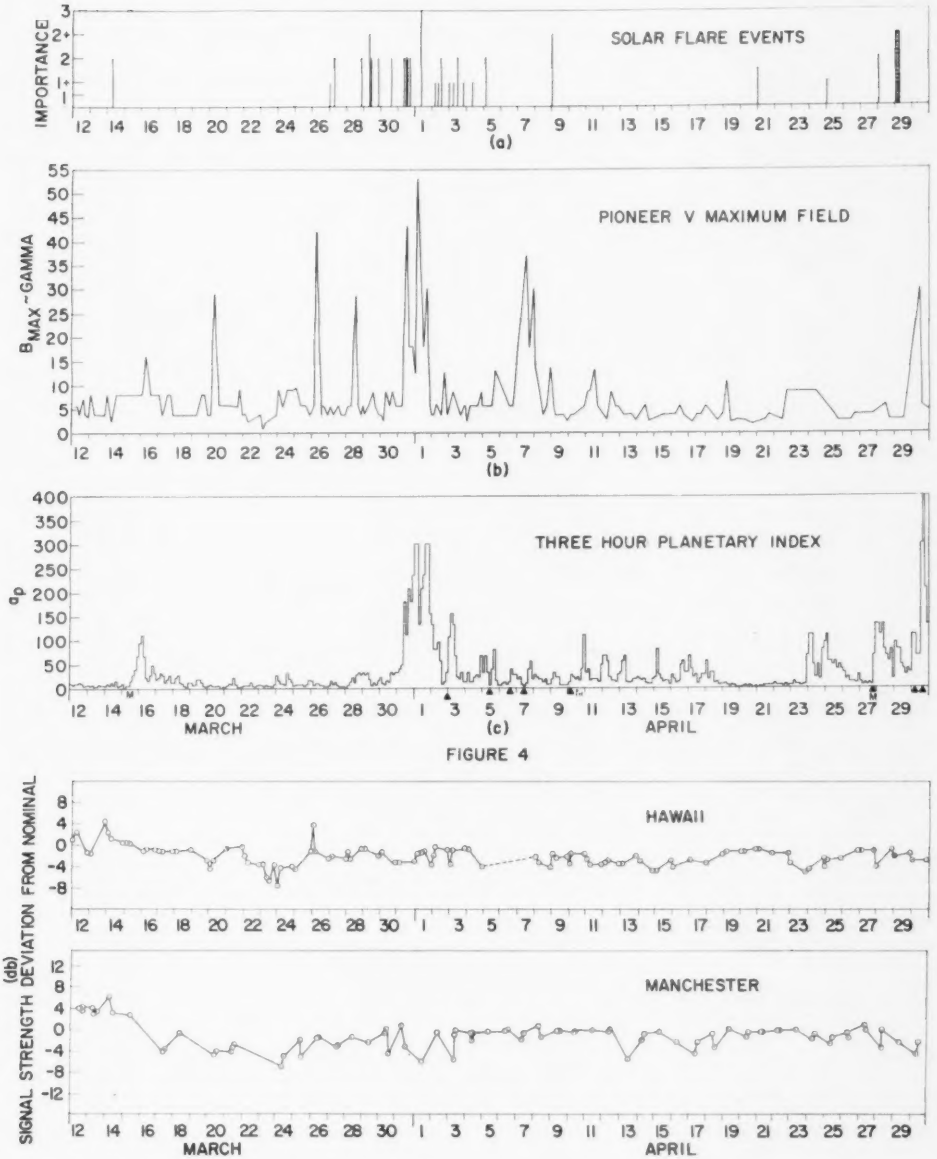


FIGURE 4

FIG. 13. Solar flare and magnetic phenomena correlation for Pioneer V.

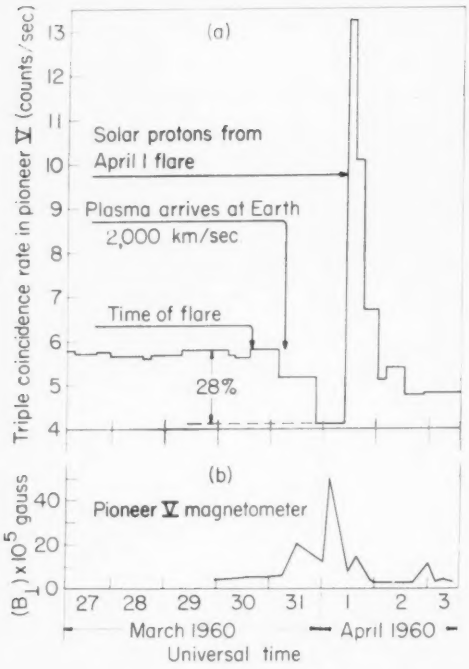


FIG. 14. Cosmic rays from the sun, showing no delay in arrival and exhibiting a forbush decrease.

radiate at many frequencies other than those capable of penetration to the surface. The OAO will contain devices sensitive to X-rays, ultra-violet and infrared radiation. First experiments will concentrate on the Lyman ultra-violet line, at 1,100 Angstroms wave length, the primary resonance of the Hydrogen atom (Missiles and Rockets, 1960). The OAO will be designed to accommodate a variety of experiment modules, and in fact will be capable of lofting a 36-inch telescope but will for some missions carry several 8-inch telescopes to prepare an ultra-violet map of the sky. This class of spacecraft, OAO, OGO, and OSO, will be standardized to the extent that only the scientific instruments will vary from mission to mission.

Space Probes, Lunar Exploration

Initially, the moon will be probed by Ranger, a hard landing system. It will impact on the lunar

Table 2. Payload Weights for Given Missions. (NASA Industry Program Plans)

Launch Date	Booster	Pounds in Orbit of 300 naut. mi.	Escape Weight (moderate capability)	Escape Weight (large capability)
1961	Atlas Agenda B	5,800	750 (lb) (lunar rough)	275 (lb) lunar orbit and return
1961	Centaur	8,500	1,450	300 (lunar soft)
1964	Saturn C-1	19,000	9,000 (manned orbit and return)	1,500 (lunar soft)
1966	Saturn C-2	50,000	15,000 (lunar manned orbit and return)	2,500 (lunar soft)
1968	Nova, prelim. (9,000,000 lb first stage)	290,000	120,000–200,000 (lunar soft)	30,000 (manned lunar landing and return)

Table 3. Space Explorations

Name	Launch Date	Mission
Explorer	1958	Geophysical satellites
Pioneer	1958	Lunar orbiters, interplanetary probes
Mariner	1961	Early planetary missions
Ranger	1961–62	Lunar hard landing
Surveyor	1963–64	Lunar soft landing
Prospector	1965	Lunar soft landing, mobile surface vehicle
Voyager	1965	Planetary orbit, droppable capsule
Man in Space		
Mercury	1961	Orbit earth, 1 man
Apollo	1966	Orbit earth, 3 men
Unnamed	1970–72	Manned lunar soft landing and return. Also unnamed, a manned lunar orbit and return

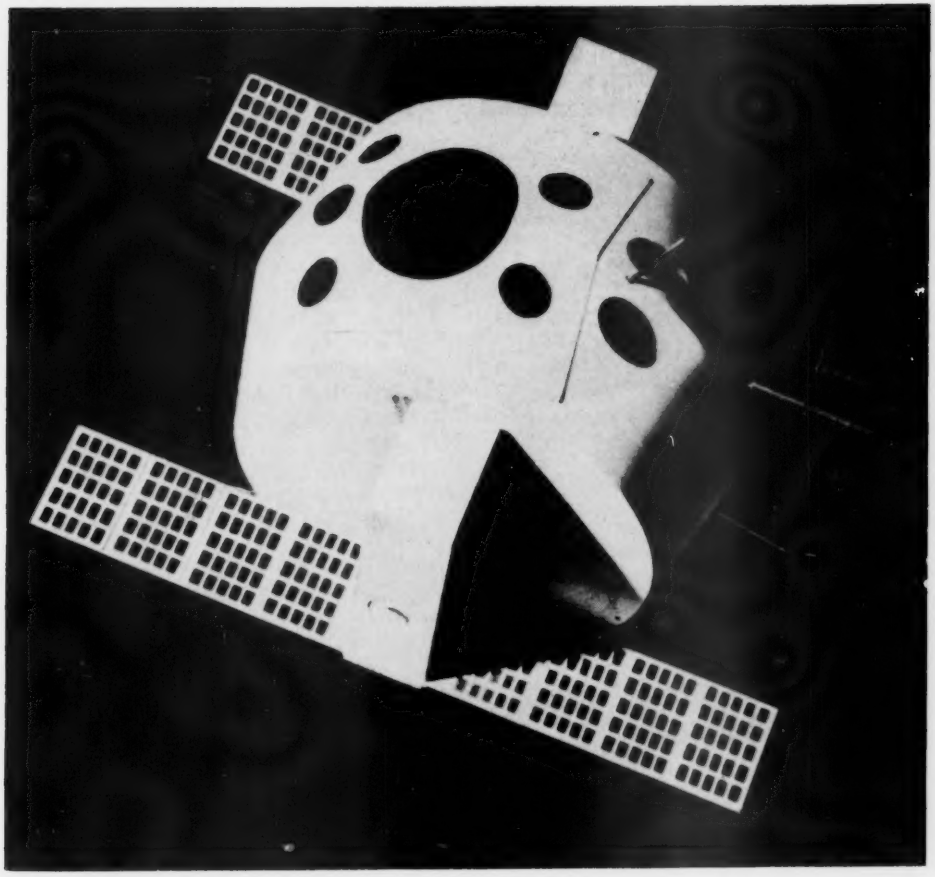


FIG. 15. Orbiting astronomical observatory.

surface at 200 to 300 mph and will contain among other instruments, a seismometer which must survive this impact and yet operate usefully. The information gained from Ranger will be used to modify the next generation of lunar landing missions and spacecraft. In addition, Ranger will be used with modifications as the first planetary probe, called Mariner. Figure 16 shows the Ranger external configuration. After Ranger will come the Surveyor. This spacecraft will be a soft landing craft. It will be boosted by the Centaur rocket configuration and will deposit a nonmobile package weighing about three hundred pounds on the surface. Surveyor is the first payload which can truly be said to explore a portion of the moon's surface and will contain a drill. Prospector, also a soft lunar landing spacecraft, is to be boosted by the Saturn and will include a mobile vehicle with a 50-mile radius of operation, see Figure 17. Finally, Voyager will be able to travel to Mars or Venus and eject a capsule, parachuted to the surface.

Requirements for Instrumentation

Spacecraft planned by NASA will require imagination and enterprise to improve the instrumentation now specified for the first generation vehicles. This is an area wherein skills acquired in terrestrial geophysical effort can contribute to the space exploration effort.

The following environmental instruments, designed for space applications are needed:

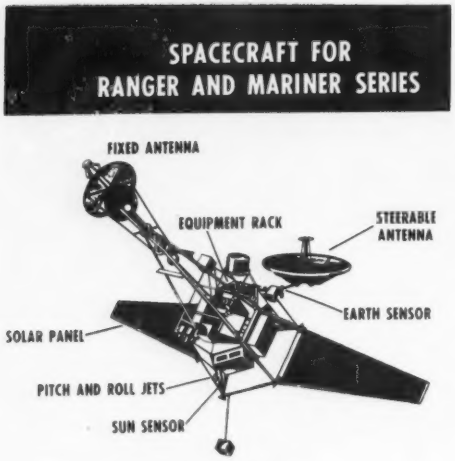


FIG. 16. Ranger spacecraft.

(1) Radiation detectors of all kinds and of all ranges of the spectrum; these should discriminate between particle species and photons;
(2) Micrometeorite detectors;
(3) Pressure, temperature, and ionization gauges;
(4) Sound detectors and analyzers;
(5) Mass spectrometers.

The observational instruments needed are the following:

(1) Television of all resolutions;
(2) Radar for height finding, contour, and surface characteristics;
(3) Spectrometers for X-rays, gamma rays, mass, and florescence;
(4) Seismometers;
(5) Magnetometers;
(6) Penetrometers and coring devices;
(7) Chemical analyzers;
(8) Microbiological equipment;
(9) Gravimeters.

Applications of Space Research in NASA Programs

Both Echo and Tiros, discussed above, are NASA programs. The follow-on to Tiros is a system called Nimbus, to be launched in 1961. Aeros, a follow-on to Nimbus, would be a system

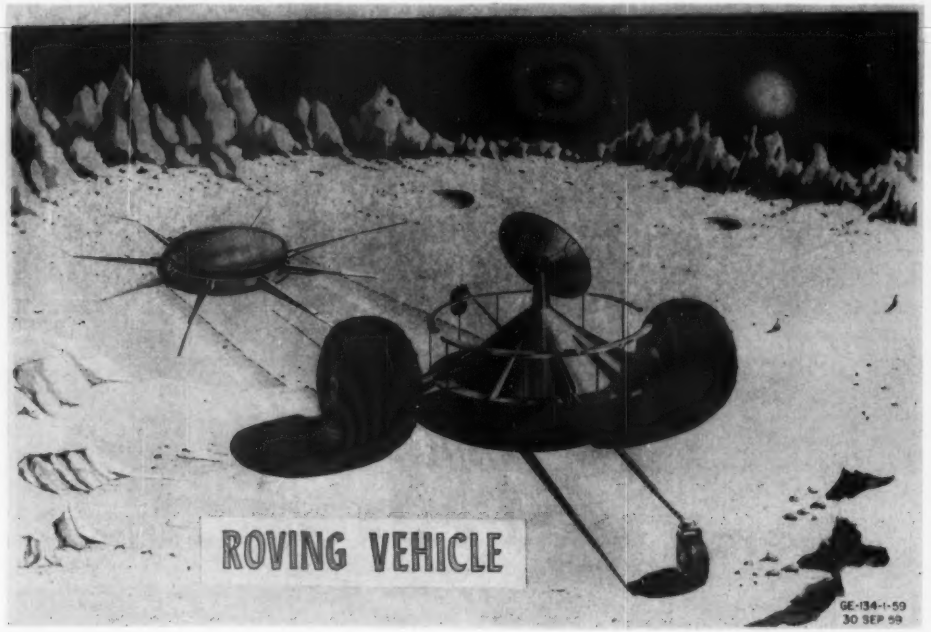


FIG. 17. Prospector.

of three 24-hour satellites to be orbited about 1964 and would permit continuous surface meteorological observations. Echo will be followed by Rebound, essentially twelve passive satellites in orbit.

SUMMARY

The initial phase of the United States space effort has been completed. The phase we are entering now results from reassessment of this program, serious effort to plan for the next decade, and, to a certain degree, from the Soviet successes which spurred our missile and payload development.

Our accomplishments have been significant; the discovery and mapping of the Van Allen radiation zones, the discovery of the terrestrial ring current, the confirmation of the part played by solar flares in the perturbation of physical phenomena occurring in the exosphere and in the earth's atmosphere, etc. These are but a few of our scientific achievements in space.

The utilization of space research for practical purposes has stimulated the initial launching of communication, meteorological, and navigation satellites. These will have considerable effects in the areas of economics, and the military.

NASA has prepared a flexible, unified, and well-rounded program for the next ten years. This program, supported by Congress and the Nation, holds promise of United States leadership in space research.

The prospects for sound, meaningful results from scientific research as a result of these programs are high. Within the next two decades, the effect upon industry and technology of space research promises to be very great indeed.

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DEPARTMENTS

LETTERS TO THE EDITOR

March 2, 1961

Dear Sir:

First, may I congratulate you and your associates on the new makeup for GEOPHYSICS. I like it very much.

Second, I very definitely approve of your choice of articles. I realize the limitations of material, but sometimes we short-haired "geo" part of geophysicists get awfully disgusted with our long-haired cousins. I wondered at times if the SEG was still for exploration geophysicists . . . .

PAUL M. TUCKER, Editor
Geophysical Society of Tulsa

January 18, 1961

Dear Sir:

I regret to advise you hereby that I am resigning my active membership of the Society. Your bulletin has become less and less readable, an increasing portion being devoted to instrumentation, and less to exploration.

P. MROSOVSKY

March 4, 1961

Mr. Peter Mrosovsky
3 Peek Crescent
London S.W. 19, England

Your letter of resignation has been referred to me inasmuch as you were kind enough to explain that you were resigning because GEOPHYSICS is becoming more "devoted to instrumentation and less to exploration" in your opinion.

ii. We are writing to sincerely ask you to reconsider your resignation in view of several facts. First of all, the Editor believes he is a practicing geophysicist and has been concerned with practical results throughout his career. His personal interests reflect such interests as you have expressed in your cause for resignation, and it is thought that some progress had been made toward making GEOPHYSICS more readable rather than less readable. For example, the 50 articles presented in the first year of this editorship are, in my opinion, 58 percent exploration and 42 percent what you call instrumentation. You may take exception to one entire issue, that of August, 1960, which was devoted entirely to logging. We thought, however, that this was definitely a practical issue in its entirety. To continue, the previous 54 articles appearing in GEOPHYSICS are, in my opinion, 28 percent exploration and 72 percent instrumentation. However, even in Dr. Faust's second year as Editor, the trend toward more practical articles began. For example, I think some of his earlier issues were entirely on "instrumentation."

iii. If you will forgive us, there is one very incriminating parting gesture, but it brings to the fore the point made by this Editor during his entire term of office. If you will read the few editorials that have appeared, you will find that it has been almost a crusade on my part to have GEOPHYSICS more readable and more practical; but the fundamental burden for practicality, once a sympathetic Editor is in office, is upon the members of the Society to provide the readable articles. To my knowledge, you, in particular, have not submitted any manuscripts to GEOPHYSICS for its consideration. I think such an act on your part would have been much more commendable than your resignation.

NELSON C. STEENLAND
Editor of GEOPHYSICS

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ISIDORE ZEITZ, U. S. Department of the Interior, Geophysics Branch, Washington, D. C.

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Anomalous Remanent Magnetization of Basalt, United States Geological Survey Bulletin 1083-E, Allan Cox, Washington, 1961, 160 pp., 20¢.

This paper describes careful experiments on a series of oriented cores from basalt flows. Very effective use is made of demagnetization phenomena in determining the nature of the magnetization of rock samples. Total magnetization can be rather clearly separated into a thermal remanent component, which is the magnetization acquired in cooling through the Curie point in the earth's magnetic field, and an isothermal remanent component which is magnetization acquired without involving a temperature change. The thermal remanent component is very much more resistive to change by demagnetization than is the isothermal component. For this reason studies of the change in magnitude and direction of the magnetic vector in various demagnetizing fields serve to separate the two components. In particular, a rather wide scattering of directions of magnetization is very greatly reduced by application of a demagnetizing field of the proper magnitude which largely removes the more or less randomly oriented isothermal magnetization and leaves the much more consistently oriented thermal remanent magnetization. Such a treatment of samples should give much better values to be applied to a large body of rocks, such as might be applicable to problems of aeromagnetic interpretation.

A detailed study of samples around an area of very anomalous magnetization indicates that the volume or cell in which this anomalous magnetization occurs is quite small with dimensions of a few tens of feet. By study of magnetization and demagnetization effects and the relations of the magnetic vectors in the samples around the anomalous area, it is inferred that the anomalous magnetization was caused by a lightning stroke with currents of the order of 22,000 amperes.

The indication, from this study, that the components of magnetization not induced by the earth's field are over small volumes is in line with observations from aeromagnetic surveys and their interpretation. Such work shows that the larger units of magnetized rock are nearly always polarized approximately in the direction of the earth's field and that other components can be ignored in quantitative interpretation of broad scale magnetic surveys.

The paper, which is from a Ph.D. thesis at the University of California, Berkeley, is well written and is documented with a bibliography of 34 titles, which is a very good set of references in this field.

L. L. NETTLETON
Gravity Meter Exploration Company
Houston, Texas

Under the Deep Oceans, T. F. Gaskell, Eyre and Spottiswoode, London, 1960, 240 pp., 25s.

The author, Dr. Gaskell, led the 1949–52 HMS *Challenger* world-wide oceanographic expedition. A veteran in underwater research, he is also Research Associate for the Exploration Department of the British Petroleum Company. He combines the points of view of both oceanographer and oil finder in this book, which is a clear, concise statement of the present status of our knowledge of the earth's crust as seen through the bottom of the sea.

The *Challenger* followed the precedent established by the famous ship of the same name in 1872–76. The modern vessel, however, established 31 formal seismic refraction stations. From there, and from daily routine reflection shots, a very notable contribution to our fund of knowledge has been made. Some mysteries were solved; others were observed which take their place.

It now appears that the famous "Andesite" line, which is almost entirely established around the Pacific, is well supported by scientific evidence and may be rather sharply delineated. As is well known, it separates the extrusions of basic rocks in the Pacific from a fringe of acidic rock bordering on the continents and takes its name from the Andes. On the Pacific side the typical 6.7 km/sec layer was observed, covered with a thin veneer (averaging 1,000 ft) of low velocity sediments. On the continental side of the line, the first main rock layer has a refraction velocity of 5.8 to 6.0 km/sec. The depth of the 8.1 km/sec layer, which marks the Moho, was always less on the ocean side of the Andesite line.

An intriguing mystery, good for an entire chapter, is supplied by the so-called Layer 2, the first hard-rock layer that sound waves encounter below the soft clay sediments of the deep sea-bed. Whereas the depth of this layer can be determined with some certainty, as can the depth of the 6.7 km/sec layer, its composition is in doubt. Layer 2 is about 3,000 ft thick and its refraction velocity varies from 5 to 6 km/sec. Its existence all over the oceans is supported by reflections. The mystery lies in its composition. Is it volcanic in origin—is there a widespread sheet of lava, a result of an enormous outpouring? Dr. Gaskell believes it is more likely that Layer 2 is for the most part a few hundred feet of limestone, resting in turn on a lower velocity layer impossible to determine by refraction work. Most probable age for this limestone, if it exists, is Cretaceous. It could be the result of enormous animal activity in the seas. The sea mounts originated in Cretaceous time, also. To further intensify the Cretaceous riddle, Dr. Gaskell points out many continental agreements in old rocks up to Cretaceous times a 100 million years ago. From this period, the rocks are dissimilar. The Cretaceous looms, then, as a truly catastrophic time of widespread sedimentation and of continental drift.

Dr. Gaskell handles the questions his own curiosity raises extremely well. For example, he builds an excellent case for the sinking, in the Pacific, of lava islands—a fate in store for the Hawaiian Islands, as well. He builds an excellent case for the Mediterranean as a continental element—but significantly he makes no mention of the equally intriguing Gulf of Mexico.

The differences between the Atlantic and Pacific oceans are great, and Dr. Gaskell explores them well. For example, there are hundreds and hundreds of sea mounts in the Pacific, but these flat-topped hills (which are sinking islands of lava) are found in only one limited area in the Northwest Atlantic. Bermuda, which might be thought to be similar in structure to the Hawaiian Islands (basic rock), is not, for a well drilled there entered andesitic rock after penetrating only 300 ft of coral. The book also contains an excellent chapter on continental drift in modern perspective and the amazing geophysical evidence which has come to its support.

Dr. Gaskell points out that all the differing lines of attack on the problem of the earth's crust are at the same time the means of improving the methods used to discover new reserves of oil.

The last chapter is devoted to the problems of deep drilling from a floating platform. Dr. Gaskell is a supporter of the proposal to drill a well to the Moho. It is interesting to note that contract has been let to drill an experimental well with slight penetration in 12,000 ft of water. Site of this well is near Guadalupe Island, off the western coast of Mexico.

The book is highly recommended as a clear-cut statement of the present knowledge and problems of oceanography and crustal studies, punctuated with delightful discourses on the rigors and rewards of the expedition which is responsible for the book.

PAUL L. LYONS
Sinclair Oil & Gas Company
Tulsa, Oklahoma

Investigation of the Mechanism of Earthquakes, E. N. Bessonova, O. D. Gotsadze, V. I. Keilis-Borok, I. V. Kirillova, S. D. Kogan, T. I. Kikhtikova, L. N. Malinovskaya, G. I. Pavlova, and A. A. Sorskii, American Geophysical Union, Washington, 1960, viii+201 pp., $7.50.

In the years 1948 to the present, the scientists of the Institute of Physics of the Earth in Moscow have developed an advanced technique for determining the character of the motion at the source of an earthquake from the data of seismograms. In 1957 a summary of the method was published under the editorship of Keilis-Borok, the foremost contributor to the work. The present translation makes available to western seismologists and other earth scientists this valuable contribution.

The book is divided into two parts. Part I presents

the theoretical basis for the methodolgy of Keilis-Borok and a condensed description of that methodology. The mathematical treatment is brief, yet sufficient detail is included to enable one to follow the development of the authors. For rigor of proof the reader is referred to the original papers. The theory of volume and point sources is reviewed and the conditions mentioned under which the two types of sources are equivalent. Then some ten different mathematical point sources are considered, each consisting of a single force, a dipole, or a multipole of one kind or another. Of all the earthquakes to which the method has been applied, however, in no case has a source been found by the Russian seismologists which requires a point model other than a dipole with moment.

The practical methodology is adequately described and supposes only a general understanding of the theory. This portion of the book, together with the Appendices, will serve as a handbook for the research seismologist interested in applying the technique. The method, in essence, is parallel to that of Byerly. It makes use of a different type of projection, however, and allows for much wider use of data other than the direction of first motion of *P*. An approach is also described whereby, independently of the directions of first motion, the amplitude ratios *SV*:*SH*, *P*:*SH*, *P*:*SV* can be used to determine the axis of motion at the source from the data of a single station, or from the data of a few stations.

Part II of the book will appeal to geologists and to tectonophysicists interested in the results of mechanism studies. A statistical analysis is given of all the fault-plane solutions determined in each of the seismic areas along the borders of the USSR. In each region a careful comparison is made between the tectonics of the region, its seismicity, and the solutions studied. Some of the conclusions are unexpected. No direct connection is found between the displacements at individual foci and local tectonic structures, including local surface faults. The earthquakes studied seem rather to be related to deep seated tectonic processes and to the basic structural peculiarities of large tectonic complexes as a whole.

The book suffers somewhat from an excessive literalness of translation and by an evident lack of familiarity on the part of the translator with the terminology involved. "Ratio," for instance, is translated throughout as "relation," "passing to the limit" as "limited transition," "plane wave" as "flat wave." Most confusing of all, ambiguous and unique solutions are rendered as solutions "not of the same sign" and "of the same sign," respectively. It is regretted that the editor did not provide for revision of the translation by one acquainted with the field; the material is worthy of the most favorable presentation.

WILLIAM STAUDER, S.J.
Saint Louis University
Saint Louis, Missouri

Séismométrie Théorique, Mme S. Duclaux, Gauthier-Villars, Paris, 129 pp., 1959, $5.50.

In her introduction, the author expresses the hope that this short treatise will prove useful to the daily operators of seismological stations by providing a homogeneous and complete presentation of the knowledge required to solve problems such as calibration, response determination, and design of seismometers. All the content of this manual can be found in many separate articles and books, but the author deserves merit for having produced a unified treatment of the subject.

In the first five chapters, the principles and basic differential equations governing the pendulum mechanical seismographs are described, followed by the derivation of the responses to both steady state and unit step and by the calibration procedure. The next two chapters cover the same theory relating to the pendulum electromagnetic seismographs including the mutual interaction (coupling) of the mechanical and electromagnetic portions. The eighth chapter describes the determination of a zero-coupling seismograph equivalent to a given seismograph satisfying stipulated conditions. After a brief survey of the major types of electromagnetic seismographs in the ninth chapter, the author gives, in the last four chapters, a very detailed exposition of:

a. How to design, with numerical examples, various seismographs with desired characteristic properties.
b. How to calibrate a given electromagnetic seismograph.
c. How to verify the calibration and proper functioning of an operating seismograph.
d. How to make various mechanical adjustments which are very important in the mounting of a new instrument.

The reviewer's lack of experience with the problems encountered in a seismographic station prevents him from giving an educated opinion on the practical value of this manual for station operators.

PIERRE L. GOUPILLAUD
Continental Oil Company
Ponca City, Oklahoma

On Two-Dimensional Waves in an Elastic Half-Space, J. W. Craggs, *Proceedings of the Cambridge Philosophical Soceity (Mathematical and Physical Sciences)*, Vol. 56, Part 3, July 1960, pp. 269–285.

The method of dynamic similarity, in which the stress, strain, and material velocity depend only on r/t and θ, is assumed for two-dimensional waves in a half-space. This assumption allows the equations of motion to be reduced to a form similar to the "cone-field" equations of linearized supersonic flow in fluid dynamics, thereby dividing the solution into arrivals before and after the direct wave.

Analytic solutions are given for both a stationary source and a source whose surface dimension expands at a constant rate. Numerical results are obtained for the vertical stress at the free surface when half the surface is step loaded (the rate of expansion of the source becomes infinite). Rayleigh waves of large amplitude are developed when the expanding rate approaches the Rayleigh velocity.

The method of solution is complicated in that it depends greatly on the intuitive ability of the investigator. However, any technique that removes the steady state assumption from elastic wave theory should be respected and explored.

J. T. CHERRY
Continental Oil Company
Ponca City, Oklahoma

Aerospace Dictionary, Frank Gaynor, Philosophical Library, New York, 1960, x+260 pp., $6.00.

Designed to cash in on the current space mania with as low an investment as possible, *Aerospace Dictionary* is a miscellaneous collection of random comments related to some terms used in popular discussions of space. An introduction by Wernher von Braun entitled *The "Why" of Space Travel*, was apparently dashed off in a spare moment or two and is the sort of high-sounding Sunday-supplement material which he so frequently dishes up. If one does not question too closely such items as the possibility of importing coal from Venus as a motivation for space exploration, it is quite easy to find one's self eagerly awaiting the chance to buy a ticket into space under the spell of von Braun's tub thumping.

Such "definitions" as are present are often at a level suitable for a not-too-bright high-school sophomore, or are simply wrong. A few examples will illustrate the level of this work:

"*ether*—In physics, the medium assumed to permeate all the space of the universe, including both the spaces between bodies and the bodies themselves, and believed to be the vehicle of propagation of light and other forms of radiation."

"*g, G*— . . . gravity on the surface of the earth that imparts an acceleration of 32 feet per second to a body in free fall . . ."

"*G-force*— . . . gravitational pull required to move a body at the rate of about 32.16 feet per second per second."

"*Kepler's laws*— . . . (3) The squares of the lines required for the different planets to complete their orbits are proportional to the cubes of their mean distances from the sun."

"*magnetostriction*—The change in the dimensions of a ferromagnetic object when replaced in a magnetic field."

"*maser*—The designation coined from the initials of the phrase 'Microwave Amplification by Stimulated Emission of Radiation,' denoting a device introduced in 1957 which, among several other applications in physics, chemistry, radio and television communication is expected to increase the utility of radio telescopes a hundredfold."

"*mass*—A measure of the quantity of matter in a body, determined by comparing the resultant changes in velocities when the body impinges upon a standard body."

"*port*—the left-hand side of a spaceship, looking from the rear to the nose." (Secretary's Note: But which way is up?)

"*terminal velocity*—The hypothetical maximum speed which a body could attain under given conditions."

The Greek alphabet is given but in a new and refreshingly different order.

No attempt has been made at completeness or consistency. For example, *nutation* has been included but *precession* does not appear at all, even though one of the alternative definitions of nutation is "any slight inequality of the motion of precession." Relativity and its ramifications (except time dilation) are completely ignored. Every bit of alphabet soup concerning missiles, however, appears to be included, even to the names and nicknames of specific missiles and satellites and of the assorted animals which have traveled in them.

Although the number of "definitions" in this "dictionary" is quite small, the publishers have managed, by using large type, generous margins and separate chapters for each letter (the three lines of definition for the two "Q" entries occupy one full page), to manufacture a 260 page book which gives the illusion of some considerable content. In standard dictionary format the entire content of *Aerospace Dictionary* could be condensed into 25 or 30 pages.

This book will not be useful to technical people in any field because of its negligible scope. It is not recommended for students or non-technical people because of gross inaccuracies and incompleteness.

CARL H. SAVIT
Western Geophysical Company of America
Los Angeles, California

PUBLICATIONS RECEIVED

BOOKS

An Introduction to Statistical Communication Theory, by David Middleton, McGraw-Hill, New York, $25.00.

Rotation of the Earth, by W. H. Munk, G. J. F. MacDonald, Cambridge University Press, $13.50.

The Precambrian Geology and Geochronology of Minnesota, by Samuel S. Goldich et al., University of Minnesota Press, $4.00.

PERIODICALS

American Journal of Science, v. 259, nos. 2 & 3 (Feb. & Mar., 1961).

Annales de Geophysique, v. 16, n. 4 (1960).

Annali de Geofisica, v. 13, n. 3 & 4 (Oct. & Dec., 1960).

Bulletin (Izvestiya), nos. 7 & 8 (July & Aug., 1960).

I' U.G.G. Chronicle, nos. 32 & 33 (Dec., 1960).

Economic Geology, v. 55, n. 8 (Dec., 1960), v. 56, n. 1 (Jan. & Feb., 1961).

Erdol und Kohle, v. 14, n. 1 (Jan., 1961).

Geophysical Abstracts, v. 182 (July–Sept., 1960).

Geophysical Digest, v. 8, nos. 1 & 2 (Jan. & Apr., 1960).

Geophysical Notes, v. 13, n. 2 (1960).

Gerlands Beitrage zur Geophysik, v. 69, n. 6 (1960).

Journal of Geophysical Research, v. 66, n. 2 (Feb., 1961).

Journal of Petroleum Technology, v. 13, nos. 2 & 3 (Feb. & Mar. 1961).

Mines Magazine, v. L1, nos. 2 & 3 (Feb. & Mar., 1961).

Mining Engineering, v. 13, n. 2 (Feb., 1961).

Physics Today, v. 14, nos. 2 & 3 (Feb. & Mar., 1961).

Proceedings of the Cambridge Philosophical Society, v. 57, Part 1 (Jan., 1961).

Quarterly Journal of the Geological Society of London, v. 116, n. 464, part 4 (Dec., 1960).

Tellus, v. 12, n. 4 (Nov. 1960).

MEMORIALS

ROBERT F. ALDREDGE

ROBERT F. ALDREDGE, geophysicist, gentleman, teacher, friend of many all over the world, loved by all who knew him, passed away in Mexico City while at work on January 23, 1961. Although his state of health had been precarious since a previous attack in 1954, his sudden demise, caused by a coronary occlusion, was quite a shock to his friends.

Bob Aldredge was born in Martins Ferry, Ohio, on October 12, 1895, the son of Madison and Dora Emily Aldredge. He was the youngest of five children, and was preceded in death by his brothers, Evers P. and Thomas M., and his sisters, Edna and Harriett. His early schooling was in St. Clairsville and Bellaire, Ohio. Bob was graduated from the Bellaire High School. After a year at Michigan State University, he enlisted in the Air Force during World War I. He became a pilot and held the rank of Lieutenant.

Upon his discharge, he was employed in surveying, inspecting, and allied fields by coal mining companies in Belmont County, Ohio. In 1928 he joined the Lakes Border Patrol as a government inspector. A year later, by working part time to pay his way, he resumed his education at Ohio State University. He was graduated in 1931 with a Bachelor of Science degree in mathematics and geology.

Having become aware of the opportunities opening up in the relatively new science of Geophysics, as applied to the search for petroleum, Bob enrolled in 1931 in the Colorado School of Mines, and in 1933 received his Master of Science degree in geophysics from that institution.

He began his career in geophysics in the Gulf Research & Development laboratory in the summer of 1933, and later spent some time for Gulf in Venezuela. In 1935 he returned to the Colorado School of Mines to teach mathematics and geology. During the summer of 1936 he worked as a party chief for Seismograph Service Corporation, and during the summer of 1937, did some research work for Heiland Research Corporation.

In the fall of 1937 Bob joined SSC as a party chief on a seismic crew, and within a month was sent to Persia, where he remained a year. From Persia he was transferred to South America and, during the next six years, spent time for SSC in Argentina, Venezuela, Trinidad, and Colombia as a supervisor and manager. When Westby Geophysical Corporation was formed in 1945 as a wholly-owned subsidiary, Bob was made a vice-president and took charge of its operations in Mexico. Here he remained until the time of his death.

A warm and generous personality, Bob had a great capacity for making and keeping friends in all walks of life. His kindly nature earned him the love and respect of his crew members of all nationalities, as well as that of his associates and members of the client organizations for whom his crews were working. He could make himself at home in any country and always discover and enjoy the cultural advantages in each country. He loved classical music, the ballet and opera but could be equally pleased by native folk-singing. He was a perfect host who not only knew how to

plan and organize a superb dinner party but also could make all his guests feel at ease.

His love of people led him into many philanthropies in which he gave much of his own time and money.

In his last assignment in Mexico, Bob found the cultural atmosphere and friends which influenced him to retire there when the time came.

Bob was a top geophysicist. He taught geophysics at the University of Mexico for several years in addition to his company duties. He was a long-time member of the Society of Exploration Geophysicists, the American Association of Petroleum Geologists, and the Asociacion Mexicana de Geologos Petroleros.

With the passing of Bob Aldredge, the geophysical profession, his business associates, and his many friends in Mexico and elsewhere have lost a man of highest integrity and character, an outstanding geophysicist, and a gentle and warm friend. Perhaps his Mexican friends best epitomized him in saying what we all felt, "Bob Aldredge is a perfect gentleman."

G. H. WESTBY

JACKSON JEFFERSON FLOWERS

JACK FLOWERS died suddenly from a heart attack December 16, 1960. He will be sorely missed by his many friends both in and out of the oil industry. Jack was born in Toyah, Texas, September 23, 1910, but he had most of his early schooling in Big Spring, Texas. From 1929 to 1933 he attended Texas Technological College, where he graduated with a B.A. degree in Geology.

He was employed by Humble Oil & Refining Company as a member of a seismic crew in West Texas on April 24, 1934, and worked for Humble the rest of his life. He performed all types of seismic work in the field, and in June of 1946 was placed in Humble's central interpretation office in Houston. In July of 1948 he was transferred to Tyler, Texas, as a member of the newly organized geophysical interpretation section. Tyler became his home.

Jack was intensely interested in his geophysical interpretations and the coordination of geophysical information with the known geologic information. He became one of Humble's outstanding geophysicists in the East Texas Area. He was a great help to younger men and gave fully of his time to help them understand and work out interpretative problems.

He will be remembered chiefly for his unfailing sense of humor. No situation was ever so tense that it could not be relieved by one of his quick, pertinent, humorous remarks. He was a happy man and made all those around him happy. He had no particular hobby, but took part in activities that offered a chance to get with other people and have a good time. He was a familiar sight working in his yard. He had a wonderful family. He and his wife, Marjorie Wilkie of Houston, were married August 6, 1938, and had three children, two sons (Michael and Woody) and a daughter (Betty Sue). In addition to his wife and children, he is survived by two sisters and three brothers: Mrs. George White of Big Spring, Texas; Mrs. F. L. Underwood of Midland, Texas; Major W. V. Flowers of Charleston, South Carolina; Robert O. Flowers of Big Spring, Texas; and Sam C. Flowers of Houston, Texas. He was a Mason and a deacon in the First Christian Church of Tyler. He was a long-time member of SEG, AAPG, and the East Texas Geological Society.

His pleasant, cheery approach to every problem and to all people will be missed by all of us, and he leaves us with the feeling that it was a privilege to have known and worked with him.

O. D. BROOKS

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,966,627. J. E. Hawkins. Iss. 12/27/60. App. 11/14/56. Assign. Seismograph Service Corp.

Method and Apparatus for Electrical Prospecting. An electrical prospecting system in which currents of different frequencies are applied to the earth at spaced pairs of electrodes and the beat signal picked up with a pair of electrodes at various locations, signals representative of the exciting currents being transmitted to the pick-up station by radio and heterodyned for reference, and the phase of the beat signal determined with respect to the reference.

GRAVIMETRIC PROSPECTING

U. S. No. 2,958,522. J. M. Slater. Iss. 11/1/60. App. 11/12/57. Assign. North American Aviation, Inc.

Sectional Stable Platform. An inertial reference system whose reference platform is made in two articulated sections each of which is gyrostabilized about two axes and controls a slaving servo that maintains a predetermined orientation between the two sections.

U. S. No. 2,959,961. F. Haalck. Iss. 11/15/60. App. 3/10/56 and 3.5.57. Assign. Askania-Werke A.G.

Gravimeter. A gravimeter having a spring-suspended mass with a hollow cylindrical extension containing a vertical fiber suspending a horizontal bar magnet between the poles of two opposing stationary horseshoe magnets, so that vertical movement of the mass effects rotation of the bar magnet which is detected by a light beam reflected from a mirror fastened to the magnet.

U. S. No. 2,964,948. L. J. B. LaCoste. Iss. 12/20/60. App. 9/30/54. Assign. LaCoste & Romberg.

Force Measuring Apparatus. A stabilized reference system having a beam suspended about a transverse axis with a long period and with an optically controlled follow-up servomotor that corrects displacement between the beam and the case, a long period being obtained by means of a labilizing spring and air damping being provided by a dash pot into which air is blown by the servosystem in accordance with the correction effected.

MAGNETIC PROSPECTING

U. S. No. 2,958,819. J. C. Bregar. Iss. 11/1/60. App. 3/25/52. Assign. Western Electric Co., Inc.

Method and Apparatus for Adjusting Magnetometers. An error correcting system for an unoriented three-component-squared type of total-field magnetometer in which the reluctance error of the individual elements is corrected by shifting small slugs of paramagnetic material on the element and the misparabolism error is corrected by an adjustable condenser across its terminals.

U. S. No. 2,959,733. L. Koch and G. Lambert. Iss. 11/8/60. App. 12/30/57 and 12/29/58. Assign. Commissariat a l'Energie Atomique.

Hall Effect Magnetometer. A Hall effect magnetometer using a single source of current which supplies current to a semi-conductor Hall-effect element and also supplies current to a potentiometer circuit with which the Hall-effect voltage is measured.

U. S. No. 2,961,604. E. A. Schuchard. Iss. 11/22/60. App. 10/11/50.

Apparatus and Method for Detecting and Recording Total Magnetic Field Gradients. A test set for determining the stray magnetic fields of component devices and having two total-field magnetometers in a bridge circuit and mounted on a tiltable beam which can be aligned with respect to the ambient field, one of the magnetometers having a platform on which the device being tested can be placed in various positions and its magnetic effect observed.

U. S. No. 2,964,700. F. W. Lee. Iss. 12/13/60. App. 7/22/53.

Magnetic Variometer. A magnetometer having two aligned rods of high-permeability material and a non-magnetic disk carrying magnetic inserts rotating between adjacent ends of the rods, the emf induced in coils on the rods being amplified, rectified, and recorded, and also fed back to additonal coils on the rods to buck out the ambient field.

* Gulf Oil Corporation, Patent Department.

RADIOACTIVITY PROSPECTING

U. S. No. 2,958,779. W. G. Spear. Iss. 11/1/60. App. 4/6/59. Assign. U.S.A.

Scintillation Exposure Rate Detector. A scintillation detector for gamma or X-rays having a photomultiplier coupled to a scintillating crystal that has a tantalum shield remote from the phototube to make the photon response independent of the energy of the incident radiation.

U. S. No. 2,960,609. F. P. Smith. Iss. 11/15/60. App. 5/13/57. Assign. International Telephone and Telegraph Corp.

Geiger Counter. A Geiger tube circuit using a low voltage battery and an amplifier and transformer arranged so that pulses through the Geiger tube generate high voltage which charges a condenser that supplies the Geiger tube voltage.

U. S. No. 2,963,588. J. A. Wilson. Iss. 12/6/60. App. 2/9/56. Assign. Esso Research and Engineering Co.

Safety Device for Radiation Level Monitor Systems. A radiation monitoring system which has a low-level source near the detector and circuits to provide both a high-level alarm and a low-level alarm, the latter providing a signal if the apparatus should fail.

U. S. No. 2,963,589. H. V. Neher and A. R. Johnston. Iss. 12/6/60. App. 4/16/56.

Automatic Ionization Chamber. An ionization chamber having a charged Insulated central electrode and a nearby elastic conducting charging fiber that is repelled when the electrode is charged but after collection of a predetermined number of ion charges the charging fiber is attracted to contact and recharge the electrode thereby effecting a signal in an external circuit.

U. S. No. 2,964,632. H. Friedman, T. A. Chubb, and J. E. Kupperian, Jr. Iss. 12/13/60. App. 4/7/55.

Coincidence-Glow Radiation Detector. A radioactivity detector having a halogen-quenched Geiger-Mueller tube and a gas glow tube connected in series to the secondary of a vibrator-type high voltage source with rectifier, coincidence of an ionizing radiation with a high-voltage pulse from the source effecting a discharge through both the G-M tube and the glow tube.

U. S. No. 2,965,757. P. W. Martin, R. W. Pringle, and K. I. Roulston. Iss. 12/20/60. App. 8/3/53.

Spectral Analysis of Material. An activation analysis system for samples or well logging using a neutron source and scintillation spectrometer whose signals are stored and analyzed as to energy distribution with selective interval between irradiation and detection, selective irradiation time, or by selective discrimination through varying the energy of bombarding neutrons.

U. S. No. 2,965,759. H. C. Eberline. Iss. 12/20/60. App. 1/16/57. Assign. Eberline Instrument Division of Reynolds Electrical and Engineering Co., Inc.

Proportional Counter. An alpha-ray detector having a chamber with a diaphragm-covered window and central insulated electrode connected to the conductor of a coaxial cable, the chamber containing gas supplied through the cable.

U. S. No. 2,965,760. J. G. Crump. Iss. 12/20/60. App. 3/19/59. Assign. Industrial Nucleonics Corp.

Radiation Measuring Device. A radioactivity detector having a Geiger-Mueller tube with a high-impedance load controlling the grid voltage of a thyratron that has a relay in its plate circuit.

U. S. No. 2,965,780. R. T. Bayard and A. G. McElroy. Iss. 12/20/60. App. 8/12/54. Assign. Westinghouse Electric Corp.

Proportional Counter. A neutron counter made of a small flat frame of insulating material with an anode suspended in the frame, a coaxial cable being attached to one edge of the frame with the cable sheath extending over and sealing the sides of the frame and with the cable wire attached to the anode.

U. S. No. 2,965,781. S. B. Gunst and R. T. Bayard. Iss. 12/20/60. App. 1/23/57. Assign. U.S.A.

Neutron-Counter. A fission counter for thermal neutrons having concentric spherical metal electrodes coated with fissionable material and using ceramic insulation for use at high temperature and pressure.

SEISMIC PROSPECTING

U. S. No. 2,958,786. E. G. Millis. Iss. 11/1/60. App. 12/16/55. Assign. Texas Instruments Inc.

Transistor Transducer. A transducer having a light source shining past a movable shield onto a phototransistor so that movement of the shield varies the light falling on the photosensitive junction of the transistor.

U. S. No. 2,958,822. D. P. Rogers and D. B. Staake. Iss. 11/1/60. App. 4/26/56. Assign. U.S.A.

Low Frequency Spectrum and Amplitude Distribution Analyzer. A system for analyzing a complex low frequency wave by recording it on a magnetic tape, playing the tape back at a high rate and rerecording on an endless tape which is repeatedly reproduced and the signal analyzed In a harmonic analyzer and the measured frequency distribution recorded.

U. S. No. 2,958,846. B. Luskin. Iss. 11/1/60. App. 6/27/58. Assign. Times Facsimile Corp.

Recording Ocean Depth. An echo sounding apparatus for use on a submarine having two transducers project-

ing pulses upward and downward, the upward transducer being pulsed first and the downward transducer pulsed when the reflection from the water surface is received by the upward transducer, and the pulses recorded to show depth of the submarine and depth of water below the submarine.

U. S. No. 2,958,849. S. J. Begun. Iss. 11/1/60. App. 10/29/54. Assign. Clevite Corp.

Multichannel Magnetic Reproducing Apparatus. A seismograph magnetic recording-reproducing apparatus having two drums on one of which the geophone signals are origianlly recorded, the separate tracks being subsequently rerecorded on a transfer drum with the transfer recording head moved in the direction of tape movement to correct for step-out.

U. S. No. 2,959,240. R. H. Schmuck. Iss. 11/8/60. App. 8/21/58. Assign. Jersey Production Research Co.

Geophysical Prospecting Apparatus. A seismometer for use in a well to profile a vertical structure and having a directionally sensitive detector and an adjustable eccentric weight rotatably mounted on an axis parallel to the borehole axis, the eccentric weight seeking the low side of the previously surveyed borehole so that the detector can be oriented to be preferentially sensitive to reflections from the boundary of the structure.

U. S. No. 2,960,176. A. L. Parrack. Iss. 11/15/60. App. 10/16/57. Assign. Texaco Inc.

Apparatus Related to Seismic Exploration. A system for eliminating seismic ghosts by filtering and attenuating the direct pulse, applying a time delay, and combining the delayed pulse in opposition to the received signal to cancel out the effect of the shot reflection at the surface of the earth.

U. S. No. 2,960,379. J. W. Lipscomb. Iss. 11/15/60. App. 11/9/56.

Method and Apparatus for Seismic Prospecting. A recorder for weight-dropping seismic operation having a rotating drum with film on which the seismic signals are recorded in variable-density form and timing signals are simultaneously put on the film.

U. S. No. 2,960,661. R. W. Bratschi. Iss. 11/15/60. App. 1/16/57. Assign. Sperry Rand Corp.

Automatic Gain Control Circuit. An avc system using a two stage gain-control amplifier with the second stage controlled to increase its amplification with increase of signal in the first stage of the gain-control amplifier thereby to hold the signal more nearly constant in the main signal channel.

U. S. No. 2,961,638. L. R. Padberg, Jr. Iss. 11/22/60. App. 4/25/55.

Magnetostrictive Electro-Acoustical Transducer. An underwater transducer having four groups of laminated magnetostrictive cores in contact with the water and wound with highly insulated windings to which the water has access to facilitate cooling, the four units being connected in a series-parallel arrangement with three terminals to provide directivity.

U. S. No. 2,962,697. G. O. Rockwell. Iss. 11/29/60. App. 4/3/46 and 3/4/58. Assign. U.S.A.

Directional Locator for Origin of Fluid Borne Vibrations. A device for indicating the direction of incidence of an acoustic pulse having pairs of hydrophones arranged in three-dimensional quadrants and connected to thyratron indicating circuits so that firing of the first thyratron of each pair applies a bias to the second to prevent its firing.

U. S. No. 2,963,647. W. C. Dean. Iss. 12/6/60. App. 5/15/58. Assign. Gulf Research & Development Co.

Electrical Transient Analyzer. Apparatus for analyzing a transient for its Laguerre components in which the transient is recorded on a magnetic record and then played back in reverse time through special filter circuits whose instantaneous output is observed at zero instant of the original record.

U. S. No. 2,963,671. M. DiGiovanni. Iss. 12/6/60. App. 8/3/59. Assign. Statham Instruments, Inc.

Transducer. A transducer having a beam supported at an angle to a frame with unbonded wire strain gages between the beam and the frame.

U. S. No. 2,963,911. J. S. Courtney-Pratt and W. P. Mason. Iss. 12/13/60. App. 2/18/59. Assign. Bell Telephone Laboratories, Inc.

Piezoresistive Accelerometer. An accelerometer having a mass and three mutually perpendicular pairs of diametrically opposing legs all made of a single crystal of a piezoresistive material and with opposing leg elements connected in opposite arms of an a-c bridge circuit.

U. S. No. 2,964,712. W. C. Dean and M. E. Taylor. Iss. 12/13/60. App. 9/29/59. Assign. Gulf Research & Development Co.

Automatically Tuned Notch Filter. An automatically tuned notch filter having a high-Q tuned filter connected in parallel with a band-pass filter and with their outputs combined differentially, the tuning of the high-Q filter being automatically adjusted from the differential output of two filters tuned on each side of the tuning range to be covered.

U. S. No. 2,964,713. F. H. Shepard, Jr. Iss. 12/13/60. App. 6/13/52 and 3/7/58.

Audio Automatic Volume Control. An avc system in which the signal is applied to one or more input tubes ahead of the amplifier and each having a resistor with

blocking condensers connected from the plate to cathode circuits and with a thermistor between the cathode and ground, the amplifier output being rectified and returned to the grids of the input tubes.

U. S. No. 2,964,730. A. Blanchard. Iss. 12/13/60. App. 2/25/55. Assign. Schlumberger Well Surveying Corp.

Electro-Acoustic Transducer Having Coaxially Spaced Cylindrical Coils. An acoustic source for an acoustic logging apparatus having concentric annular coils embedded in a nonmagnetic material, the coils being spaced radially but mechanically connected at the ends, and electrically energized so that the outer coil expands when the inner coil contracts.

U. S. No. 2,964,731. J. J. Coop. Iss. 12/13/60. App. 6/18/54.

Long Line Condenser Hydrophone with Gaseous Pockets. A condenser-type hydrophone having a metal strip sandwiched and sealed between two strips of insulating material, with an outer larger sheath of flexible insulating material having an air space between the sheath and the inner strips, so that the acoustic pressure compresses the air and varies the capacitance between the ambient conducting liquid and the metal strip.

U. S. No. 2,964,732. R. H. J. Geneslay. Iss. 12/13/60. App. 10/12/57 and 10/2/58. Assign. Compagnie Generale de Geophysique.

Seismograph. An axially symmetrical reluctance-type seismometer having an axial permanent magnet wound with a coil and having a symmetrical armature suspended on an axial spring wire extending from the side of the case facing the magnet so that the armature can move only at right angles to the axis of symmetry to change the air gap in the magnetic circuit completed by the case.

U. S. No. 2,964,837. W. T. Harris. Iss. 12/20/60. App. 6/9/58. Assign. The Harris Transducer Corp.

Method of Transducer Manufacture. A method of mounting a magnetostrictive transducer by inserting its ends into sockets of a metal having a higher coefficient of thermal expansion than the transducer, and filling intervening space with a thermosetting bonding material, so that upon proper cooling the assembly is rigidly held in position.

U. S. No. 2,965,876. G. Meunier and C. Bruant. Iss. 12/20/60. App. 10/31/53 and 10/25/54. Assign. Societe Alsacienne de Constructions Mecaniques.

Compensated Sonic Echo Ranging System. An echo sounding system that includes an analog computer whose parameters are adjusted for known variation of velocity with depth so as to give a corrected distance indication.

U. S. No. 2,965,877. J. H. Stein and J. D. Wallace. Iss. 12/20/60. App. 6/10/57. Assign. U.S.A.

Capacitive-Type Line Hydrophone. A condenser-type hydrophone having a metal strip covered by a latticed insulating sleeve with air pockets between the lattices and enveloped in a water-tight flexible insulating plastic sheath so that the acoustic pressure acting on the trapped air varies the capacitance between the ambient liquid and the metal strip.

U. S. No. 2,966, 656. C. R. Bigbie and E. A Pence, Jr. Iss. 12/27/60. App. 8/2/56. Assign. U.S.A.

Spherical Electro-Acoustic Transducer with Internal Heater. A hydrophone made of two hollow hemispheres of barium titanate having metalized inner and outer coatings which form electrodes, and an internal electric heating element to maintain the temperature in a region where changes of temperature have little effect on the resonant frequency.

U. S. No. 2,966,657. J. F. Price. Iss. 12/27/60. App. 3/31/49. Assign. U.S.A.

Acoustic Direction Finder. An acustic direction finding system using two bi-directional cosine-law microphones in quadrature and an omni-directional microphone connected to a c–r tube indicator with the beam brightness-control circuit arranged to increase brightness when desired frequencies are received and decrease brightness upon the arrival of interfering frequencies.

WELL LOGGING

U. S. No. 2,958,780. J. T. Dewan. Iss. 11/1/60. App. 10/29/56. Assign. Schlumberger Well Surveying Corp.

Methods and Apparatus for Investigating Earth Formations. A radio-activity logging apparatus having a borehole accelerator employing the D–T reaction at a target, an alpha-particle detector being located laterally of the target and a gamma-ray detector below the target, the alpha-particle detector being connected to a time-delay circuit and to a coincidence circuit with the gamma-ray detector, coincidence indicating effects in the formations caused by neutrons from the target in the lateral direction opposite to the side on which the alpha-particle detector is located.

U. S. No. 2,959,241. F. P. Kokesh. Iss. 11/8/60. App. 12/8/55. Assign. Schlumberger Well Surveying Corp.

Apparatus for Investigating Earth Formations. An arrangement for supporting an acoustic logging transducer on a cable in which the transducer housing has releasable clamps that hold it on one side of the cable and employing separable electrical connectors.

U. S. No. 2,960,608. F. C. Armistead. Iss. 11/15/60. App. 4/27/56. Assign. Texaco Development Corp.

Radiological Well Logging. A neutron logging sonde having the source and detector mounted on arms that are resiliently urged into contact with the borehole wall and with several annular neutron-absorbing shields intermediate the source and detector, the shields having staggered openings to permit passage of borehole fluid.

U. S. No. 2,960,651. C. B. Scotty. Iss. 11/15/60. App. 12/3/56. Assign. Texaco Inc.

Electric Logging System. An electric logging system using one current electrode and a pair of closely spaced potential electrodes a considerable distance above the current electrode and a second pair of closely spaced potential electrodes a considerable distance below the current electrode, the resistivity as determined with both pairs of potential electrodes being simultaneously recorded.

U. S. No. 2,961,539. E. F. Egan, G. Herzog, and J. C. Allen. Iss. 11/22/60. App. 11/14/55. Assign. Texaco Inc.

Productivity Well Logging. A method of identifying fluids entering a well at various levels by measuring the gamma-ray absorption of the well fluid with a gamma-gamma density logging sonde having an outer shield to eliminate effects of the borehole wall.

U. S. No. 2,961,544. A. H. Youmans, R. Monaghan, B. F. Wilson, and T. A. Henrichs. Iss. 11/22/60. App. 8/2/56. Assign. Well Surveys, Inc.

Source Shield for Density Logging Instruments. A gamma-gamma density logging sonde having an outer steel housing containing gamma-ray absorbing material and with the source contained in an inclined tube and the detector in an axial bore with a window on the same side of the housing as the source.

U. S. No. 2,961,600. D. R. Tanguy. Iss. 11/22/60. App. 10/30/56. Assign. Schlumberger Well Surveying Corp.

Electrical Well Logging Apparatus. An electrode pad that is pressed against the borehole wall and that has a central current electrode and an annular focusing electrode and a potential-measuring electrode between them.

U. S. No. 2,961,602. J. C. Bender. Iss. 11/22/60. App. 7/3/50, 5/12/54 and 8/10/54. Assign. Houston Oil Field Material Co., Inc.

Method of and Apparatus for Determining Physical Properties of Materials. A system for locating the point where pipe is stuck in a well by lowering into the pipe an r–f oscillator coupled to the pipe while the pipe is stressed and observing at the surface changes in the frequency of the oscillator.

U. S. No. 2,962,895. R. C. Rumble. Iss. 12/6/60. App. 10/28/57. Assign. Jersey Production Research Co.

Fluid Meter. A well flow meter having an impeller-driven shaft magnetically coupled to a shaft rotating in a sealed chamber and having a photoelectric revolution counter, the impeller shaft having a magnetic suspension and the magnetic coupling having a debris guard to prevent fouling.

U. S. No. 2,963,582. T. W. Bonner and R. L. Caldwell. Iss. 12/6/60. App. 11/8/54. Assign. Socony Mobil Oil Co., Inc.

Neutron Production Through Alpha Disintegration of Carbon 13. A radioactivity logging method in which neutrons are produced by a mixture of an alpha rayer such as polonium or plutonium with carbon 13, the formations being logged for carbon by detecting gamma rays of 4.4 mev. energy.

U. S. No. 2,963,583. M. P. Lebourg. Iss. 12/6/60. App. 1/17/55. Assign. Schlumberger Well Surveying Corp.

Well Logging Apparatus. A radioactivity logging device in which the radioactive source is contained in a buoyant capsule that is free to move in an unsealed portion of the sonde so that the source-detector distance is automatically decreased when the device is used in a liquid-filled borehole.

U. S. No. 2,963,584. J. M. Thayer and R. E. Fearon. Iss. 12/6/60. App. 7/30/49, 6/24/55, and 6/28/55. Assign. Well Surveys, Inc.

Pulse Height Analyzer. A neutron-neutron logging system using a pulse-height discriminator having a c–r tube whose beam is deflected by the pulses, with pulses that reach a selected portion of the c–r tube screen being detected.

U. S. No. 2,963,586. J. A. Rickard. Iss. 12/6/60. App. 10/18/56. Assign. Jersey Production Research Co.

Method of Logging Wells by Induced Delayed Radiation. A neutron-gamma logging system having a fast neutron source and detector with pulse-height analyzer, the source-detector distance and the logging speed being adjusted so that the gamma rays are detected an interval after passage of the source that is equal to the half-life of a selected element.

U. S. No. 2,963,587. J. A. Rickard. Iss. 12/6/60. App. 4/29/55. Assign. Jersey Production Research Co.

Method of Well Logging. A neutron-delayed gamma radioactivity logging system using a number of detectors each with pulse-height discriminator and spaced from the source by various distances arranged so that at the normal logging speed the detector for a particular element traverses a region of the borehole the half-life interval after passage of the source.

U. S. No. 2,963,640. G. O. Buckner, Jr. Iss. 12/6/60. App. 3/4/57. Assign. Welex, Inc.

Well Bore Resistivity Scanning System. An electric logging system using two closely spaced current electrodes and a number of potential electrodes at increasing distances to one side of the current electrodes, the measuring apparatus automatically recording at each depth unit the potential difference between each potential electrode and a distant reference electrode.

U. S. No. 2,963,644. E. D. Nuttall. Iss. 12/6/60. App. 9/19/56. Assign. United Gas Corp.

Methods of and Apparatus for Determining the Wall Thickness of Metallic Elements. A magnetic testing device having a magnet whose flux enters the material being tested and having a coil that moves between the magnet and the material so that variations in flux due to variations in the material produce an emf in the coil.

U. S. No. 2,963,646. W. G. Hicks and J. Zemanek. Iss. 12/6/60. App. 6/2/58. Assign. Socony Mobil Oil Co., Inc.

Time Interval Measurement. An acoustic velocity logging system in which the time interval between the arrival of the pulse at two detectors is determined from the time between transition points of the two waves.

U. S. No. 2,964,116. E. W. Peterson. Iss. 12/13/60. App. 5/26/55. Assign. Dresser Industries, Inc.

Signaling System. A well signaling system having in the drill collar two flexible sleeves traversed by the drilling fluid with a piston-actuated valve between the sleeves, and a hydraulic system that employs the pressure difference between the sleeves to energize hydraulic fluid behind the sleeves for actuating the valve.

U. S. No. 2,964, 697. W. F. Ghiselin, Jr., M. E. Martin, and O. R. Smith. Iss. 12/13/60. App. 10/10/58. Assign. Welex, Inc.

Well Logging System. A multi-curve electric logging system which takes SP, several spacings of normal, and several spacings of lateral measurements over a single-conductor cable by using various signaling frequencies and sychronously driven relays.

U. S. No. 2,964, 698. A. E. Lehmberg, Jr. Iss. 12/13/60. App. 6/30/58. Assign. Schlumberger Well Surveying Corp.

Borehole Investigation Apparatus. An induction logging sonde having a fluid-tight sleeve around the sensing element filled with silicone fluid that communicates with the well fluid through a bellows to provide pressure equalization.

U. S. No. 2,964, 699. L. T. Perriam and S. S. Goldberg. Iss. 12/13/60. App. 9/9/57 and 9/5/58. Assign. Imperial Chemical Industries, Ltd.

Probe Device for Flaw Detection. A magnetic tubing tester having an axial high-permeability core with three annular pole pieces and two coils connected in an a-c bridge circuit, the outside of the housing having copper sleeves at the ends beyond the pole pieces to reduce axial spreading of the flux.

U. S. No. 2,965, 031. E. Johns. Iss. 12/20/60. App. 10/11/57. Assign. Seismograph Service Corp.

Well Bore Detector and Perforating Apparatus. A casing perforator having a radioactivity detector above it on a cable, the detector being separated and the perforator simultaneously clamped to the borehole wall by means of small explosive charges so that the cable and detector may be withdrawn, after which the perforator is fired by a self-contained time clock.

U. S. No. 2,965,753. R. C. Reynolds and A. S. McKay. Iss. 12/20/60. App. 12/8/55. Assign. Texaco Inc.

Productivity Well Logging. A well flow meter having a pair of transverse flexible barriers to isolate a portion of the formation from which the fluid passes through a tapered vertical flow tube having a radioactive float whose position is detected, and with the density of the fluid measured by means of a fixed gamma-ray source and detector.

U. S. No. 2,965,837. J. E. Hawkins. Iss. 12/20/60. App. 11/14/56. Assign. Seismograph Service Corp.

Method and Apparatus for Electrical Well Logging. An a-c electric logging system in which electrical phase changes are detected by having an auxiliary oscillator in the sonde and heterodyning the source oscillator and the auxiliary oscillator, and also heterodyning the picked-up potential with the auxiliary oscillator signal, and determining the phase changes in the picked-up potential by comparing the heterodyned signals.

U. S. No. 2,965,838. T. L. Kister. Iss. 12/20/60. App. 4/3/57. Assign. Texaco Inc.

Electrical Logging System for Exploring Subsurface Formations. An electric logging system having an electrode pad that may be retracted or pressed against the borehole wall, the pad having closely spaced electrodes for measuring mud resistivity when in the retracted position and more widely spaced electrodes for measuring the resistivity of the invaded zone when pressed against the borehole wall.

See also Patent 2,965,757 listed under RADIOACTIVITY PROSPECTING; and Patents 2,959,240; 2,964,730, and 2,964,837 listed under SEISMIC PROSPECTING; and Patents 2,964,634 and 2,964,665 listed under MISCELLANEOUS.

MISCELLANEOUS

U.S. No. 2,958,986. E. J. Krack. Iss. 11/8/60. App. 8/18/59. Assign. Gulf Research & Development Co.

Apparatus for Grinding a Magnetic Signal Transducing Head. A device for holding a magnetic recording-reproducing head in the proper azimuth during grinding-in of the head and providing a nonmagnetic wire that may be brought into engagement with the head accurately at right angles to the axis of the grinding wheel, the head being adjusted in azimuth to zero signal when a-c is passed through the wire.

U. S. No. 2,959,677. C. F. Robinson and W. M. Brubaker. Iss. 11/8/60. App. 5/2/57. Assign. Consolidated Electrodynamics Corp.

Gas Analysis. An ionization chamber for analyzing gas in which the gas flows between two electrode plates and is illuminated by selected ionizing radiation with the outer part of the chamber shrouded by a protective gas to eliminate wall effects, and the ionization current being measured and indicated.

U. S. No. 2,963,641. R. H. Nanz. Iss. 12/6/60. App. 8/1/58. Assign. Shell Oil Co.

Exploration of Earth Formations Associated with Petroleum Deposits. A geophysical prospecting method in which a trend is determined from a statistical analysis of the predominant direction of orientation of grains in the formation as observed from a core sample of known orientation by measuring the azimuthal variation of acoustic velocity diametrically through the core, or by making horizontal acoustic velocity measurements in various azimuths in a borehole.

U. S. No. 2,963,642. J. L. Arbogast, C. H. Fay, and S. Kaufman. Iss. 12/6/60. App. 8/1/58. Assign. Shell Oil Co.

Method and Apparatus for Determining Directional Dielectric Anisotropy in Solids. A method of determining the predominant direction of orientation of grains in a core sample by rotating the core on its axis between the plates of an electric condenser connected in an a-c bridge circuit and observing the azimuthal variation of dielectric effect.

U. S. No. 2,963,649. W. H. McLellan. Iss. 12/6/60. App. 8/26/57. Assign. Consolidated Electrodynamics Corp.

Galvanometer. A galvanometer element that may be inserted in a multi-element magnet block and measures the product of two signals, the element having two rigidly connected suspended coils each in a set of pole pieces that are wound with stationary field coils, with one signal passing through the suspended coils and the other signal through the stationary coils, the connections being arranged so that torque due to the permanent field is cancelled.

U. S. No. 2,963,650. J. L. Fisher. Iss. 12/6/60. App. 2/26/59. Assign. Century Geophysical Corp.

Galvanometer Suspension. A moving coil oscillograph in which damping is effected by passing the suspension ribbons through open-ended cylinders holding damping oil by capillary forces and with the suspensions carrying near each end of the cylinders beads of nonwettable material that keep the damping oil from creeping.

U. S. No. 2,964,376. W. B. Hansel and E. T. Young. Iss. 12/13/60. App. 2/16/56. Assign. Sun Oil Co.

Odograph. A vehicle odograph having an azimuth gyro on a pendulum and arranged to record on a chart on a drum that rides on a sleeve and is connected to a counterbalancing weight inside the sleeve so as to counterbalance inertial forces on the drum.

U. S. No. 2,964,634. S. P. Harris. Iss. 12/13/60. App. 6/14/55. Assign. Tracerlab, Inc.

Apparatus for Producing Neutrons. A D–T reaction discharge type neutron source having a glass tube with metal end caps that serve as targets and with ring electrodes near the ends of the tube connected to a high voltage a-c source, each target being connected to the adjacent ring electrode through a resistor.

U. S. No. 2,964,665. J. M. Brinkerhoff and S. P. Harris. Iss. 12/13/60. App. 12/1/55. Assign. Tracerlab, Inc.

Pressure Control System. A system for controlling a discharge-type neutron source in which the primary current to the discharge supply transformer is connected to a relay which turns on the pump when the discharge current exceeds the optimum value.

U. S. No. 2,965,434. G. W. Downs. Iss. 12/20/60. App. 4/1/57. Assign. Consolidated Electrodynamics Corp.

Recording Oscillograph. A beam intensifier for photographically recording a c-r oscilloscope in which the electron accelerating voltage is increased at low frequencies in proportion to the derivative of the amplitude of the deflecting signal, and at high frequencies is increased by a steady voltage proportional to the amplitude of the deflecting signal.

U. S. No. 2,966,223. V. E. Gleasman. Iss. 12/27/60. App. 3/25/57. Assign. The White Motor Co.

Motor Vehicle for Traversing Irregular Terrain. A truck that rolls on low pressure pneumatic cylinders mounted on chain-driven shafts carried on pivoted arms whose movements are controlled by a hydraulic system so as to properly distribute the load between cylinders when traversing rough ground.

SELECTED LIST OF U. S. PATENTS ISSUED DURING NOVEMBER AND DECEMBER OF 1960

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2,958,953	16	2,960,608[a]	304	2,961,652	16
2,958,986[a]	224	2,960,609[a]	308	2,961,653	316
2,959,054–055	148	2,960,610	308	2,961,767	68
2,959,057	4	2,960,611	224	2,961,772	444
2,959,059–060	16	2,960,649–650	228	2,961,870	496
2,959,082	428	2,960,651[a]	116	2,961,871	440
2,959,088	444	2,960,661[a]	372	2,961,872	428
2,959,240[a]	360, 376	2,960,678	200	2,961,874	148
2,959,241[a]	360, 376	2,960,686	224	2,962,109	484
2,959,350	68	2,960,690	68	2,962,200	224
2,959,375	16, 68	2,960,692	316	2,962,214	68
2,959,378–380	16	2,960,771	444	2,962,217	68
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2,959,636	224	2,960,873–877	16	2,962,339	224
2,959,643	224	2,960,906	16	2,962,340	324
2,959,675	372	2,960,930–931	48	2,962,558–560	224
2,959,676	236	2,960,932–933	136	2,962,588	236
2,959,677[a]	168	2,961,156	68	2,962,590–592	308

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

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2,962,614–615	308
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2,962,694	12
2,962,695	484
2,962,696	12
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2,962,893	428
2,962,895[a]	144, 148
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2,962,901	16
2,962,997	12
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2,963,579	68
2,963,580	196
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2,963,583[a]	304
2,963,584[a]	304
2,963,585	140
2,963,586[a]	304
2,963,587[a]	304
2,963,588[a]	308
2,963,589[a]	308
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2,963,635	16
2,963,640[a]	116
2,963,641[a]	88
2,963,642[a]	88, 116
2,963,644[a]	220
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2,963,646[a]	8
2,963,647[a]	360
2,963,649[a]	160
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2,964,595–597	484
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2,964,665[a]	308
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2,964,697[a]	116
2,964,698[a]	148
2,964,699[a]	220
2,964,700[a]	232
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2,964,704	68
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2,964,713[a]	372
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2,964,731[a]	484
2,964,732[a]	376
2,964,837[a]	484
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2,964,941	292
2,964,942	288
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2,965,433	324
2,965,434[a]	324
2,965,435	12
2,965,466	136
2,965,703	68
2,965,708	224
2,965,720–723	224
2,965,753[a]	148, 292
2,965,757[a]	304
2,965,758	308
2,965,759[a]	308
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2,965,781[a]	308
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2,965,877[a]	484
2,965,878	12, 484
2,965,879	12
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2,965,888	200
2,965,894	16
2,965,895–896	316
2,966,056–058	12
2,966,059	252
2,966,061	188
2,966,090	444
2,966,133	148
2,966,223[a]	490
2,966,302–307	68
2,966,359	224
2,966,360	484
2,966,558	484
2,966,587	308
2,966,590	308
2,966,599	68
2,966,612	196
2,966,613	308
2,966,617	4
2,966,627[a]	124
2,966,628	188
2,966,656[a]	484
2,966,657[a]	12
2,966,666	224
2,966,667	288
2,966,673	68, 484
2,966,675	312
2,966,676	316, 444

CONTRIBUTORS

R. A. BAILE

R. A. BAILE received his B.S. degree in Mathematics from Central Missouri State College in 1942. Following graduation he entered the Air Force and in 1946 was discharged as a 1st Lt., having served as an Engineering Officer and Flight Engineer. He then joined Pan American Petroleum (then Stanolind Oil and Gas Co.) as a Computer on a seismograph crew. During the period of 1946 to 1952 he held a series of positions, the final one being that of Seismograph Supervisor in Pan Am's Midland office. In the Spring of 1952, he resigned his position with Pan Am to join in the forming of Empire Geophysical. At present he is Executive Vice President of Empire. Mr. Baile is a member of the SEG, PBGS, and WTGS.

L. C. CUMMINGS, JR.

L. C. CUMMINGS, JR., attended Tyler Jr. College (1941–42), the University of Minnesota (1947), and the University of Texas (1948–50). He was employed by the Humble Oil & Refining Company in January 1952 and served on a seismic crew until August 1955. He worked for a short period with Humble's Geophysical Engineering group before being assigned to his present position with Geophysical Research. Mr. Cummings is a member of the Society of Exploration Geophysicists and the Institute of Radio Engineers.

RUSSELL L. GRAY

RUSSELL L. GRAY, a native of Utah, received his B.S. degree in Geophysics in 1959 and M.S. degree in Geophysics in 1961, both from the University of Utah. He worked for Western Geophysical Company and Pan American Petroleum Corporation during the summers of 1957 and 1958, respectively, and was a University of Utah Geophysics Department research assistant engaged in crustal studies during the summer of 1959. He is now associated with the Research and Technical Department of Texaco Inc., Bellaire, Texas.

Mr. Gray is a member of SEG and Sigma Xi.

MARTIN G. GUDZIN served in the U. S. Navy during World War II, and was assigned to the Naval Ordnance Laboratory where he was engaged in unstrument maintenance and calibration work. At this time he began his engineering studies at George Washington University.

Following his discharge from service, Mr. Gudzin enrolled at Rensselaer Polytechnic Institute from which

MARTIN G. GUDZIN

JACK H. HAMILTON

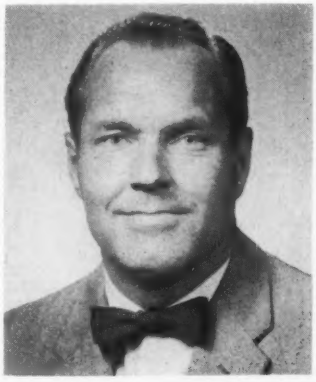
he received a B.S. degree in electrical engineering in 1949. Upon graduation, he returned to the Naval Ordnance Laboratory where he assisted in the development of fluxgate magnetometers. Later the same year he joined the firm of Beers and Heroy as an instrumentation engineer. This was followed in 1951 by work with W. & L. E. Gurley where he devoted further efforts to optical and magnetic instrumentation, and the development of linear and angular measuring systems. In 1953 Mr. Gudzin rejoined The Geotechnical Corporation (successor to Beers and Heroy) where he developed improved seismic amplifiers and recorders. He became a project engineer shortly thereafter and supervised the development of a ground-based FM telemetering system for low frequency analog data. Today, as senior research engineer of the Systems Engineering Section, he is responsible for the development of integrated seismic detection, recording and reduction systems. He also oversees seismic research and study programs, and supervises field trials for instrumentation and systems.

Mr. Gudzin's professional affiliations include memberships in the Institute of Radio Engineers and the Dallas Geophysical Society.

JACK H. HAMILTON served with the U. S. Navy during World War II, and enrolled at George Washington University upon his release from service. He was graduated in 1949 with a B.S. degree in mechanical engineering.

As a design engineer in the firm of Beers and Heroy, he developed shaking tables for the calibration of seismograph systems, and designed intrumentation for the analysis of seismic data. In 1951 he joined W. & L. E. Gurley Company where he developed optical micrometers, theodolites, and shaft-to-digital encoders. This was followed in 1952 by his return to The Geotechnical Corporation (successor to Beers and Heroy) as a project engineer. In this capacity he supervised development of seismometers, galvanometers, recorders and complete data-reduction systems. Mr. Hamilton became Chief Engineer and Manager of Research in 1955. Since 1959 he has served as Vice-President and, as such, supervises the technical and operational functions of the company, takes an active part in customer liaison, and is a key member of management. He also served as a member of the Panel on Seismic Improvement (Berkner Panel) under the auspices of the Special Assistant to the President for Science and Technology in 1959.

Mr. Hamilton is a registered professional engineer in the State of Texas and a member of the American Society of Mechanical Engineers, Seismological Society of America, American Geophysical Union, Institute of Radio Engineers and the Dallas Geophysical Society.



PETER JACOBSEN, JR.

PETER JACOBSEN, JR., graduated from Dartmouth College in Geology in 1941, with honors; did post-graduate work in 1941–42 in geology and geophysics at California Institute of Technology; joined The Carter Oil Company in 1942 and served in various capacities on geophysical field crews; transferred to Creole Petroleum Corporation in 1946; employed in various phases of geophysical interpretation from that date until October 1960, with title of Chief Geophysical Interpreter from 1948 on; now head of Geophysical Interpretation Research Section of Jersey Production Research Company. He is a member of SEG, AAPG, AGU, Sigma Xi, European Assoc. of Exploration Geophysicists, Asociacion Venezolana de Geologia, Mineria y Petroleo, Sociedad Venezolana de Geofisica.

J. R. LISHMAN

J. R. LISHMAN graduated from the University of Leeds, England in 1951 with an honours degree in geology. He was engaged in gravity work in Iraq with Robert H. Ray Company, until moving to Canada in 1953 to work in the seismic department of Imperial Oil. In 1954 Mr. Lishman joined the California Standard Company, and has worked in geophysics, geochemistry, and geology, before taking up his present position as senior formation evaluation geologist in 1959. Mr. Lishman is past-president of the Canadian Well Logging Society.

ALLEN J. MCMAHON received a B.S. degree from Carnegie Tech in 1947. Upon graduation, he joined the staff of the Brookhaven National Laboratories, and performed work on cosmic ray research. He joined M.I.T. in 1950 as a research assistant, and completed research on cosmic rays under the direction of the Cosmic Ray Group of the Physics Dept. He joined the Hughes Aircraft Co. in 1952 as a research physicist and completed a series of studies on missile systems. He joined the staff of the Space Technology Laboratories, Inc., in 1960 as a

ALLEN J. MCMAHON

member of the technical staff in the R. and D. Division. Mr. McMahon is presently staff physicist in the Orbiting Geophysical Observatory Program Directorate.

F. N. TULLOS

F. N. TULLOS earned the B.S. in E.E. degree from Louisiana State University in 1936. He was employed by the Humble Oil & Refining Company in June of 1936 and served on a seismic crew until October 1941. In October of 1941 Mr. Tullos obtained a leave of absence and entered Carnegie Institute. He later transferred to Johns Hopkins University (Applied Physics Laboratory) to supervise field testing of the proximity fuse. He returned to Humble in October 1945 and has served since then in Geophysics Research. Mr. Tullos is a member of the Institute of Radio Engineers and the Acoustical Society of America.

Biographies of the following authors appear in earlier issues of GEOPHYSICS as follows: K. L. Cook, v. 26, p. 119; T. C. Richards, v. 23, p. 380.

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with By-laws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

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J. D. Tomlinson (R. H. T. Schut, S. Prins, G. Lievano)

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Michael A. Clevenger (E. Joe Shmek, S. J. Allen, B. W. Sorge, R. A. Peterson)

Thomas J. Ellis (W. E. Heinrichs, Jr., Dart Wantland, R. A. Lowery, G. E. Tarbox)

Claude I. Lloyd (Joe H. Jones, J. H. Ransom, J. F. Johnson, D. D. Goddard)

T. O. May (J. A. Harris, M. G. Frey, I. B. Murray, A. F. Barker)

James E. Moore (V. H. Waddell, B. J. Sorrells, C. B. Smith, P. H. Ledyard)

Harry R. Nicholls (John H. Baade, W. B. Robinson, Flint Agee, Wilbur I. Duvall)

Eddie L. Nix, Jr. (D. P. Melton, H. H. Happel, Jr., R. L. Galloway, Vernal Clark)

John Parkin, III (P. R. LeTourneau, R. E. Doan, J. W. Garhart)

Lorne H. Reed (R. B. Ross, G. J. Blundun, P. J. Savage, J. C. J. Fuller)

Michael S. Reford (Dr. L. W. Morley, H. J. Kidder, R. H. Pemberton, H. Jensen)

Charles R. Scoggins (W. J. Fennessey, J. W. Bolinger, Robert E. Watson)

Cleo E. Vague (S. W. Furehling, A. J. Barthelmes, J. W. Hammond, B. G. Baugh)

ANNOUNCEMENTS

NEW STUDENT SOCIETY OF SEG

The Missouri School of Mines and Metallurgy Student Society of SEG was chartered October 28, 1960, at a dinner meeting in Rolla. EDWIN J. BALLANTYNE, JR. (left), President, received the certificate of charter from RALPH D. LYNN (right), President of the Geophysical Society of Tulsa, making his the eleventh student society to affiliate with SEG. The other officers are Robert W. Piekarz, Vice-President, Bruce G. Weetman, Secretary; and Howard F. Gaines, Treasurer. Dr. Hughes M. Zenor, Professor of Geophysics, is Faculty Advisor.

The installation committee from the Geophysical Society of Tulsa was composed of G. H. Westby, Chairman, Paul L. Lyons, Ralph D. Lynn, and Colin Campbell. Mr. Lyons gave the illustrated talk, "A History of Geophysics and the SEG," which was received with enthusiasm by the faculty, as well as the students. Mr. Westby spoke briefly on the opportunities for geophysicists. Mr. Lynn charged the group to support the objectives of the student society and the SEG. Campbell's job was to prepare the certificate; he "went along for the ride."

CANADIAN SOCIETY OF EXPLORATION GEOPHYSICISTS ELECTS NEW OFFICERS

The newly elected officers of the Canadian Society of Exploration Geophysicists, installed at the Annual Meeting in the Palliser Hotel, Calgary, on February 27, 1961 are: Front row, left to right: JACK M. DESMOND, Western Geophysical Company of Canada, Vice-President; PETER I. BEDIZ, Century Geophysical Corporation of Canada, President. Back row, left to right: NASH H. MILLER, United Geophysical Company of Canada, Treasurer; MILTON B. DOBRIN, Triad Oil Company, Past President; RODNEY J. H. SMITH, Imperial Oil Limited, Secretary.

NEW API PUBLICATION

Safe Practices in Geophysical Exploration Operations, a new safety publication by the American Petroleum Institute is now available from the API Publications Department.

The booklet is intended primarily to cover details of seismic operations. The basic principles, however, can apply to other phases of geophysical exploration. The suggestions are in advisory form.

Operations covered by separate sections are: general, surveying, shot hole drilling, shooting, recording, marsh and swamp operations, helicopter operations, Marine operations, and an appendix on nitro carbonitrate blasting agents.

The bulletin is printed in two sizes: 8 in. by $10\frac{1}{2}$ in., and $3\frac{3}{4}$ in. by $6\frac{3}{4}$ in. Copies at $1.00 each can be obtained from the Publications Department, American Petroleum Institute, 1271 Avenue of the Americas, New York 20, New York.

KANSAS GEOLOGICAL SOCIETY TWENTY-SIXTH ANNUAL FIELD CONFERENCE, SEPTEMBER 14, 15, AND 16, 1961

The 1961 Kansas Geological Society Field Conference has been scheduled for the 14, 15, and 16 (Thursday, Friday, and Saturday) of September. Headquarters for the conference will be Mark Twain's home at Hannibal, Missouri, on the Mississippi River. The main objective of the conference will be to study the boundary problems of the Lower Mississippian rocks in Missouri and Illinois. Leadership for the trip will be supplied by the Missouri and Illinois Geological Societies jointly.

Start making your plans to attend now in order to assure a good attendance and a successful field conference in September.

TULSA FIRM TO USE CONOCO'S SEISMIC EXPLORATION SYSTEM

Selection by Continental Oil Co. of Seismograph Service Corp., Tulsa, Okla., as a licensee for "VIBRO-

SEIS" exploration service, Continental's new system of seismic exploration, has been announced.

Seismograph Service, a geophysical contracting firm, will offer this new system of seismic exploration in certain foreign areas, the announcement stated. The new method was developed by Continental research and exploration personnel and has been successfully tested during the past several years in the company's own domestic exploration program.

"The 'VIBROSEIS' system is regarded by many geophysicists as one of the most significant breakthroughs in seismic exploration science in the past two decades," said President L. F. McCollum of Continental. "In this system, vibrators on the surface of the earth are used to generate seismic waves, instead of utilizing buried explosive charges or dropping weights as is presently done."

G. H. Westby, president of Seismograph Service Corp., said his firm's world-wide organization would integrate the new "VIBROSEIS" system into its exploratory work.

Under the system, new model vibrators allow the geophysicist to control closely the signal sent into the earth, the announcement said. This gives him a choice of the signal best suited to the geologic conditions of the area he wishes to explore.

DALLAS GEOLOGICAL AND GEOPHYSICAL SOCIETIES ANNOUNCE PUBLICATIONS

The availability of four publications which will be of interest to members of the petroleum exploration industry has been jointly announced by the Dallas Geological and Geophysical Societies, co-sponsors of the publications.

The Geology and Geophysics of Cooke and Grayson Counties, Texas is a 211-page symposium containing 54 illustrations of selected oil fields in that area, stratigraphic cross-sections, structure maps, electric logs, regional gravity maps, well velocity information, reflection seismic data and other pertinent information. It is available at $10.00 per copy.

The Geology of the Ouachita Mountains has as its co-sponsor the Ardmore Geological Society. It is a 207-page symposium with 72 illustrations presenting the depositional and structural setting of the western Ouachitas. A 68-page field trip guidebook with road log and 33 photographs is included in the $10.50 price.

An interesting and informative *Texas Geological Highway Map* is available, rolled for $1.25 and folded for $1.00. This eleven-color map is 35×28 inches. It shows surface geologic information, highways, principal towns and landmarks.

Also available for distribution is the combined *Photo-Directory* of the Dallas Geological and Geophysical Societies. Listings are given alphabetically by member and company affiliation. Price is $2.25.

All prices are postage paid, and supplies are limited. Inquiries should be directed to Mr. J. E. Bryant, Dallas Geological Society, Dept. AAPG, 1200 Vaughn Building, Dallas 1, Texas.

GEOPHYSICAL SYMPOSIA REPRINT AVAILABLE

The Oklahoma City Geological Society announces the availability of a reprint containing papers presented at a symposium on Seismograph Dip Migration held in September, 1957 and a symposium on Continuous Velocity Logging held in May, 1959. The price of the reprint is $2.00 plus postage and handling.

Address your order to: Circulation Manager, P. O. Box 609, Oklahoma City, Oklahoma.

ABSTRACTS

Bulletin (Izvestiya) July, 1960, Academy of Sciences, U.S.S.R., Geophysics Series.

Thermal Deformations of the Earth's Surface

V. V. Popov

On the Value of the Ratio of the Velocities of Longitudinal and Transverse Waves in Rocks. I

L. V. Molotova and Yu. I. Vassil'ev

The paper examines the existing methods of determination of the ratio of the velocities of longitudinal and transverse waves in rocks and suggests several new methods for the determination of this parameter. Examples of the determination of v_P/v_S from field experimental data are adduced.

A Study of Electrical Resistance in Samples of Rocks at All-Around Pressure up to 1000 kg cm²

M. P. Volarovich and A. T. Bondarenko

Methods are described for determining the electrical resistance of rock samples at all-around pressure up to 1,000 kg/cm² for direct current. It was found that the resistance alters most at pressures up to 400 kg/cm². Along with the residual and true resistance, for all the rocks studied the magnitude of the electromotive force of polarization at 1 and 1,000 atm was measured; the course of the change in its value with the pressure was also determined.

Asymptotic Expressions for Electromagnetic Fields Caused by a Cylindrical Inhomogeneity

B. P. D'Yakonov

Asymptotic expressions are obtained for the anomalous electromagnetic fields occurring at a considerable distance from a cylindrical inhomogeneity lying deep below the earth's surface.

Borehole Percussion Device for the Excitation of Various Types of Elastic Waves

O. I. Kovalev and L. V. Molotova

This paper discusses the construction of a percussion borehole device whose effect is analogous to the effect of a horizontal force applied in a given direction. Results of tests are discussed of the borehole percussion device under field conditions. Data are given on velocities of longitudinal and transverse waves *SV* and *SH* in sandy clay rocks composing the upper portion of the profile, 0–30 m.

The Use of Magnetic Powder in Studying the Composition of Iron Ores

M. A. Grabovsky, O. N. Zherdenko and Yu. P. Skovorodkin

Paleomagnetic Subdivision of the Marguzar Section of the Cenozoic Continental Molasse Beds

A. A. Valiev

The Relation Between Chromosphere Flares and Geomagnetic Activity

O. M. Barsukov

The Calculation of the Vertical Gradient of a Two-Dimensional Magnetic Field

V. N. Strakhov

CONCLUSIONS

The proposed graphical method of calculating the gradient $\partial Z/\partial y$ for a two-dimensional problem yields values with an accuracy that is completely satisfactory in practice.

The results obtained show that at the present time, in the majority of cases of two-dimensional anomalies, it is not necessary to carry out special measurements of the vertical gradient.

The Magnetic Susceptibility of Ferrous Quartzites of the Starooskolsk Iron Ore Region of the Kursk Magnetic Anomaly

V. V. Konaev and T. A. Martynova

Solution of Some Two-Dimensional Problems in Electrical Prospecting

A. M. Gluzmann and N. A. Plokhikh

Several Results of Observations of Deformations of the Earth's Surface at the Geophysical Station "Yalta"

V. V. Popov and M. K. Chernyavkina

Third Conference on Paleomagnetism

Bulletin (*Izvestiya*) August, 1960, Academy of Sciences, U.S.S.R., Geophysics Series.

Velocity Ratio of Longitudinal and Transverse Waves in Rocks, II

L. V. Molotova and Yu. I. Vassil'ev

The dependence of the velocity ratio of the longitudinal and transverse waves v_P/v_E on the frequency in a heterogeneous medium is considered. The authors present and discuss a tabulation of the v_P/v_S values in rocks.

On Degenerated Head Waves in an Elastic Medium with an Interface

L. P. Zaitsev

The paper analyzes an axially-symmetric problem of forced oscillations in a medium consisting of two elastic half spaces with a plane interface. In case of liquid media oscillations of this type were identified by the author from a general solution in another paper. Their existence was previously pointed out by Červený.

A Solution of a Basic Problem in the Theory of the Induction Method of Electromagnetic Surveying

V. I. Dmitriev

A rigorous solution is obtained for the problem, basic in the theory of the induction method of electromagnetic surveying, of the diffraction of an electromagnetic field at a perfectly conducting half-plane lying in a homogeneous, conducting half-space.

An Investigation of the Dynamic Features of Longitudinal Waves in Layers of Different Thickness

O. G. Shamina

The dynamic features of longitudinal pulse waves are investigated in a free layer and in a layer immersed in water. It is shown that the velocity, form, dominant period and attenuation of a sliding wave in a free layer and a head wave from a layer in water are dependent on the thickness of the layer. The thinner the layer, the less will be the distance from the radiator within which it can be treated as a plate. The behavior of the wave amplitude is the most reliable indication that a longitudinal wave propagated in a layer with a velocity equal to the velocity in the plate is fully formed.

Methods for Controlling the Density and Elasticity of a Medium During the Two-Dimensional Modeling of Seismic Waves

B. N. Ivakin

The article examines methods for controlling the density and elasticity of thin plates (sheets) by means of a net of holes or elevations, as well as by means of fabricating a plate of variable thickness.

Map of the Youngest Tectonic Movements in Central Asia

M. V. Gzovsky, V. N. Krestnikov, N. N. Leonov, I. A. Rezanov and G. I. Reisner

The authors discuss a method for construing a map of the tectonic movements in Central Asia which shows the total vertical crustal displacement during Neogene and Quaternary.

Recordings of Water Waves in Regions of the Boundary of the Shadow Zone, Which Is Generated by Ocean Bottom

S. M. Zverev

Properties are investigated of waves which are generated from refracted water waves beyond the point of emergence of the ray which grazes the bottom of the ocean. Experimental data on the attenuation is compared with theoretical data, calculated for various models. On the basis of the comparison, conclusions are made concerning the nature of the observed waves.

On Investigations of the Gamma-Ray Spectrum of Natural Rock Layers

M. D. Friedmann

Investigation of the Attenuation of Elastic Waves in Rock Specimens

M. P. Volarovich, A. I. Levykin and V. P. Sizov

CONCLUSIONS

1. A device is developed for the investigation of the attenuation of elastic ultrasonic waves in rock specimens of small size, intended for conduction experiments made under conditions of high uniform pressures.

2. A method of determining the amplitude coefficient of attenuation is developed by the use of multiple reflections of ultrasonic pulses of a certain frequency in specimens which have a cylindrical shape.

3. Values are obtained for the attenuation coefficient of longitudinal ultrasonic waves in some rock specimens.

On the Theory of Electromagnetic Frequency Sounding of Multilayered Structures

Yu. N. Kozulin

CONCLUSIONS

1. The existing rigorous methods for computing electromagnetic fields in layered media are either formal solutions from which no physical information can be derived, or require the use of high-speed computers. It is thus necessary to develop simplified (approximation) methods of computation.

Our "effective-field" method, which compares the actual field excited in a layered half-space with the field

in a fictitious homogeneous half-space having a frequency-dependent conductivity enables us to derive very simple approximate formulas for calculation.

2. The new method is used to perform certain calculations and to suggest a principle that can be followed in constructing templates for interpreting geoelectric measurements.

The proposed technique of interpretation is also extremely simple, so that we may expect its rapid acceptance for geoelectric investigations.

The Positions of the Poles During the Tertiary Period as Determined from the Remanent Magnetization of Rocks in Northern Fergana

A. A. VALIEV

Observations with Strongly Overdamped Gravimeters, on Airplanes and Helicopters

E. I. POPOV

A Miniature Illuminator the (MO) for Recording Measurements of Tilt and for Seismic Observations

A.N. SKUR'YAT

Seismology in Yugoslavia

On the Theory of Scattering of Electromagnetic Waves on the Sea-Surface

V. I. MIKHAILOV

Conference on Heliogeophysics

PERSONAL ITEMS

DANIEL Y. KIM has been appointed division consulting geophysicist for Pan American Petroleum's central division, it was announced by Geo. W. Clarke, vice president and division manager.

Mr. Kim will occupy a new position in the company's division office, headquartered in Oklahoma City.

Born in Inchon, Korea, Kim attended Kyong-gi high school and Seoul National University in Seoul, Korea. He came to the United States in 1949, where he attended the University of Utah and received the degrees of B.S. and Ph.D. in geophysics. While at the University of Utah, he was an instructor in geophysics.

Kim joined Pan American as a geophysicist at Casper, Wyoming in 1955. He has served in staff and supervisory positions in geophysical work at Salt Lake City, Tulsa, Denver and Oklahoma City.

He is a member of the Society of Exploration Geophysicists, European Association of Exploration Geophysicists and Sigma Xi. His parents reside in Seoul. He is married and has two sons.

NAMCO INTERNATIONAL, INC., Dallas-headquartered geophysical exploration company, announces the appointment of W. J. HARKEY as its resident manager in Adelaide, South Australia. Mr. Harkey will supervise a seismic exploration program which Namco is to conduct for Delhi Australian Petroleum Limited.

Mr. Harkey has been associated with the Namco organization and related companies since 1937 and has supervised geophysical crews since 1948 in many domestic, offshore and foreign seismic exploration assignments. Prior to this latest appointment, Harkey was for 2½ years Namco's resident manager in Tripoli, Libya. Mr. Harkey, his wife, and three children will take up residence in the city of Adelaide.

MR. MORRIS E. DAYTON resigned his position as Division Geophysicist for Texas Pacific Coal and Oil Company's Canadian Division and is presently engaged in Geological and Geophysical consulting work in Sherman, Texas.

THE BOLIVIAN GULF OIL COMPANY has recently moved its operations offices and installations from Cochabamba to Santa Cruz and the residence office of C. H. DRESBACH, General Manager, to La Paz.

DR. IVAN I. MUELLER was appointed Assistant Professor of Geodesy at The Ohio State University October 1, 1960.

He is teaching Physical Geodesy, Celestial Methods in Geodesy, and Geodetic Astronomy.

Dr. Mueller received his Dipl. Eng. degree at the Technical University of Budapest, Hungary, and his Ph.D. degree in Geodesy at The Ohio State University. After graduation in 1952 he was appointed Instructor, later Assistant Professor of Geodesy at the Technical University of Budapest. After his arrival in this country he worked as a Design Engineer at C. H. Sells Consulting Engineers and Surveyors in New York City. Since January 1, 1959, he has served The Ohio State University as an Instructor until his recent appointment. He is also a Research Associate at The Institute of Geodesy. Photogrammetry and Cartography of the Ohio State University.

In addition to several publications, his professional activities include membership in the following societies: Sigma Xi, American Geophysical Union, Society of Exploration Geophysicists, American Congress on Surveying and Mapping, and Society of American Military Engineers.

DR. RICHARD A. GEYER, who has been with the Gravity Department of GSI since 1954, is now Manager of Gravity Operations, with headquarters in Houston, Texas.

DR. WILLIAM C. KNUDSEN has been appointed Senior Research Physicist in the Geophysics Research Section, La Habra Laboratory. In this position he will study basic rock physics and the application of hydrodynamic principles to petroleum exploration problems. Knudsen joined the staff of the La Habra Laboratory in 1954.

DR. WILLIAM B. AGOCS, formerly Director of Geology and Geophysics of Aero Service Corporation and affiliates, has established offices in Philadelphia as a natural resources evaluation consultant (domestic and foreign) utilizing geological-geophysical survey procedures.

A. L. MCCAHAN, formerly Head, Geophysics Section of the U. S. Navy Hydrographic Office, has been redesignated Head, Gravity Branch of a newly organized Marine Sciences Department within this Office.

HERBERT J. BREWER returned from eight years in France with ESSO R.E.P. to rejoin the Carter Division of the Humble Oil and Refining Co., as a geophysicist in the Tulsa office. During his eight years in France, he held the position of Chief Geophysicist from 1952 to

1958, and as assistant Exploration Manager from 1959 to July 1960, when he returned to the United States.

MICHAEL S. REFORD has been named chief geophysicist for the Aero Service Group, it was announced by Aero Service Corp., Philadelphia.

Reford joined Canadian Aero Service Ltd. five years ago to direct survey planning and operations, and the interpretation of airborne geophysical data. Presently he is engaged in the planning and technical direction of airborne geophysical survey programs in Australia, Egypt, Morocco, Uganda, Chile, Canada and the United States.

Previously he had worked for five years for Mobil Oil of Canada Ltd., supervising gravity, magnetic and seismic surveys, and finally being placed in charge of their geophysical operations in Western Saskatchewan. Earlier he was engaged in geophysical research projects at the Dominion Observatory, Ottawa, and at the University of Toronto.

A graduate of the University of Oxford, with a B.A. degree after studying Mathematics and Engineering, Reford earned his masters degree in Geophysics at the University of Toronto.

Reford is a member of the Society of Exploration Geophysicists, American Geophysical Union, and the European Association of Exploration Geophysicists. Also the Canadian Society of Exploration Geophysicists, Canadian Exploration Geophysical Society, and the Corporation of Professional Engineers of Quebec. He is also past president of the Ottawa Geophysical Discussion Group.

DONALD D. ROOSE, formerly Supervisor with Seismograph Service Corporation of Mexico, is now offering independent geophysical contracting services in the fields of mining, hydrology, and civil engineering. His new address is Esquina Puebla y Xalapa, Colonia Guadalupe, Tampico, Tam., Mexico.

R. M. DREYER, formerly Asst. Chief Geologist, Reynolds Metals Co., and Chief Geologist, Kaiser Aluminum, and J. K. BROOKE, formerly Administrative Mining Engineer, Kaiser Aluminum, announce the formation of a consulting practice in mining geology, mining geophysics, and mining engineering with offices at 465 California Street, San Francisco, California.

CHARLES L. ROBINSON has returned to the home office of the Robert H. Ray Company, Inc. of Houston, Texas, after spending the past year in Paris, France as Co-Manager of Geografrance, French affiliate of the Ray Company and Compagnie Generale de Geophysique, organized a year ago for weight dropping seismic operations in the French areas. Mr. Robinson will act as co-ordinator of operations between the Ray Company and Geografrance, which now has four crews operating in Algeria and Tunisia

DR. CHARLES C. BATES has assumed the duties of Chief, VELA UNIFORM Branch, Office of Nuclear Test Detection, Advanced Research Projects Agency, at the Pentagon in Washington, D. C.

GEORGE B. NOWOTNY, JR., resigned from the Humble Oil Co. and is now a partner in the firm of Barton and Nowotny, Consulting Geologists, Ft. Smith, Arkansas.

DONALD E. DINKINS resigned from Honolulu Oil Corp. to enter consulting geology, specializing in the Northern Rocky Mountain region. He is located in Billings, Montana.

H. R. FRANK, President of Applied Magnetics Corporation in Goleta, California, has announced the appointments of J. M. CUNNINGHAM as Vice-President in charge of the newly formed Instrument Division, and R. E. NORRIS as Marketing Manager. Mr. Cunningham and Mr. Norris were both formerly with Techno Instrument Company in Los Angeles.

ALFRED LOHNBERG (LARONNE) of Kfar Shmaryahu, Israel, formerly radar consultant to the Government of Mexico and with Unesco's technical Assistant Mission in Mexico, has accepted an appointment as Technical Advisor to U. N. Headquarters in New York. He is with the Resources Section of the Department of Economic and Social Affairs.

NOTES ON CALGARY CONFERENCE

Some notes on the Calgary conference, EXPLORATION GEOPHYSICS—TODAY AND TOMORROW, were taken by your Business Manager, who had the rare privilege of being on the program. The Society is deeply indebted to the members of the Canadian Society of Exploration Geophysicists, our Calgary Section, for their leadership in presenting a program on such timely and controversial subjects. Milton B. Dobrin and H. J. Kidder led the members of this very active section in projecting, planning and conducting this conference. Some features of program planning fairly new to the SEG were successfully used, and are worthy of note here.

NOTE TO PROGRAM CHAIRMEN: The Program Committee for the Calgary conference decided first what topics they wanted to hear discussed. Then they subdivided each topic into four or five sub-topics. They chose appropriate titles for the sub-topics, which then became the titles of the papers or reports to be given. The titles of the main topics became the subject-titles of the sessions.

By this time the program committee had discussed fairly thoroughly the subjects to be presented to the conference. With this knowledge of the subjects they selected the individuals they considered best equipped to discuss each. Then the chairman wrote to each of the

Participants in the Calgary Conference

Front row (l. to r.): F. A. Van Melle, W. T. Born, L. R. Newfarmer, H. J. Kidder, F. A. Hale.
Back row (l. to r.): J. C. Hollister, C. C. Campbell, M. B. Dobrin, P. L. Lyons, T. A. Link, J. P. Woods, D. M. E. McLarty, C. M. Moore, Jr., N. R. Paterson, D. C. Jones.

prospective authors, asking him to speak on the subject chosen for him, and explaining something of the nature of what the committee would like him to cover.

T. A. LINK, President, Cree Oil of Canada Ltd., Calgary, spoke at the luncheon. Entertaining, as always, Dr. Link said he opposes strongly encouraging students to study for careers in geology and geophysics, because less than 10 percent of those who have been so trained are suited for these professions.

W. T. BORN, Director of Laboratories, Geophysical Research Corp., Tulsa, spoke on "Technical Limitations of Present Geophysical Tools." He said the geophysicist should consider all techniques and methods as his tools, and the primary function of any such tool is the elimination of noise in any form that obscures the information he seeks.

F. A. VAN MELLE, Manager, Geophysical Dept., Shell Development Co., Houston, spoke on "Current Research to Improve Effectiveness of Standard Geophysical Methods." His was a highly technical presentation which we are not qualified to review.

NORMAN R. PATERSON, Chief Geophysicist, Hunting Survey Corp. Ltd., Toronto, spoke on "Trends and Prospects in Mining and Engineering Geophysics." He said present trends include: "accelerated emergence of new methods, mainly of greater complexity and higher cost; shift from contracting to mining company, from commercial to government and from small mining company to large company or syndicate operations; less emphasis on the large survey and more intensive work on smaller areas; detailed work around existing mines; and increased use of combinations of methods."

D. C. JONES, Vice-President for Production, Hudson's Bay Oil and Gas Co. Ltd., Calgary, spoke on "Alternative Employment for Geophysicists in the Oil Industry." He said geophysicists have a broader educational background than any other profession in the oil business. Some areas for application of this knowledge are: formation evaluation, automatic production systems design, corrosion prevention and control, and computer programming.

JOHN C. HOLLISTER, Head of the Department of Geophysics, Colorado School of Mines, Golden, spoke on "Impact of the Present Slump on Geophysical Education." He said job opportunity and cost of education have an important bearing on the students' selection of careers. In geology and geophysics undergraduates are declining sharply, while the number of graduate students is rising. In geophysics alone the number of undergraduate students is declining at the rate of 10 percent per year. Among other disciplines electrical engineering and physics students are increasing, while pe-

troleum engineering is declining. The cost of education is expected to double within the next 10 years. He suggests the SEG "Careers in Exploration Geophysics" present a broader picture of the applications of geophysics, that corporations forego wholesale termination of employment, and that geophysicists quit being pessimistic.

COLIN CAMPBELL, SEG Business Manager, reported that a survey of the membership showed 1.7 percent unemployed in December, 1960.

There were some other features of the conference one might consider innovations that were used successfully. ADVANCE MAIL REGISTRATION eliminated congestion and thus enabled the meeting to *start on time*. "BUY YOUR OWN DRINK" at the social hour eliminated financial loss and unnecessary fund solicitation.

A very nice custom is observed by the Calgary, Edmonton and Regina sections. At the close of each regular meeting a member of the section, previously chosen by the chairman, is called upon to express to the speaker(s) the thanks of the group for appearing before them.

Now, about the program . . .

GRAHAM B. MOODY, Petroleum Consultant, Berkeley, California, and former President of AAPG, had been invited to speak on "Influence of World Oil Reserves on Exploration Economics." He was absent on advice of his physician after a series of physical check-ups. In his place MR. D. M. E. MCCLARTY, Petroleum Consultant, Denver, spoke on "Geonomics." He said exploration is committing "economic suicide," that crude prices are down and the cost of finding new reserves has risen. He said exploration is only one of five oil-finding methods, and the competition is stiff. He proposed reorganization of the exploration effort in companies with the object of making money in the business of finding oil.

LEO R. NEWFARMER, Exploration Manager, Shell Oil Co., Houston, spoke on "Geophysics' Share of Today's Exploration Dollar." Using wildcat wells and reflection seismograph activity as indices of expenditures in oil exploration, he predicted that wildcats would require 30 percent of the future exploration budgets, geology 33 percent, geophysics 20 percent, and land 17 percent.

PAUL L. LYONS, Chief Geophysicist, Sinclair Oil & Gas Co., Tulsa, spoke on "Economics of Geophysics in Oil Exploration." He said 300 billion bbls. of oil must be found by 1975. Comparing the costs of seismic crews by areas he noted that in the United States the average crew costs about $250,000 a year, and in Canada $600,000 or more. He used Babson's industry growth curve to show that oil is still a growing industry.

CHARLES M. MOORE, Vice-President, Geophysical Service Inc., Dallas, spoke on "Problems of the Geophysical Contractor." Some problems he mentioned are: client companies tend to consider price above value in selecting a contractor; over-capacity of contractors (10 percent have left the oil business in the past year; 15 percent are not now operating. So 25 percent of the contractors operating a year ago have no market for their services); high research costs (he recommends cooperative research); seasonal demand; capital costs; and lack of understanding on the part of client oil companies.

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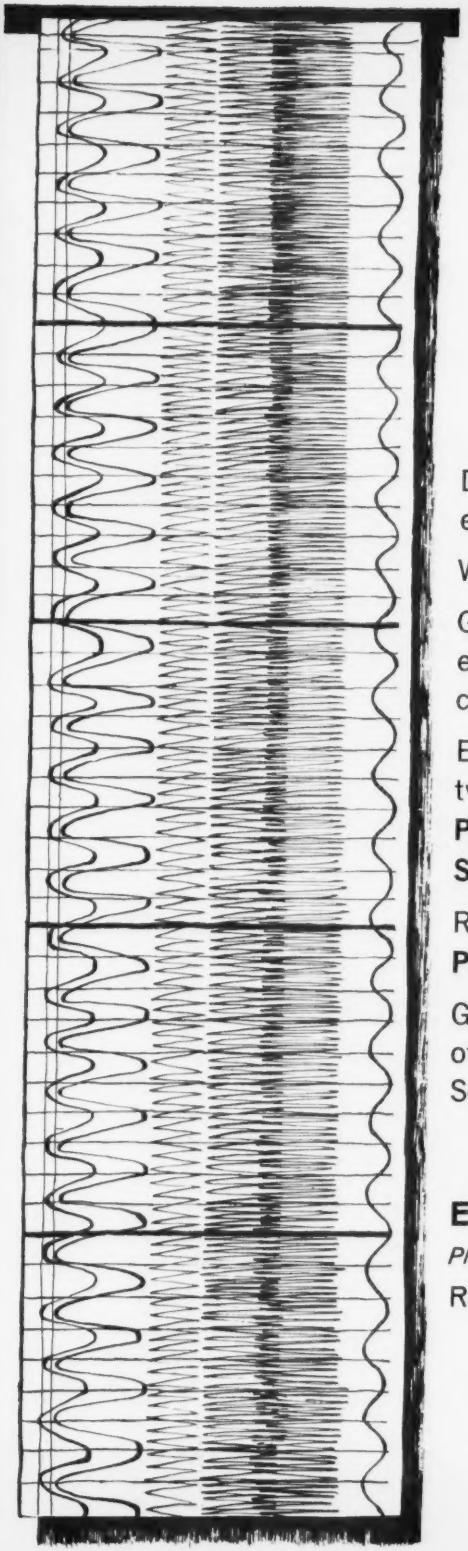

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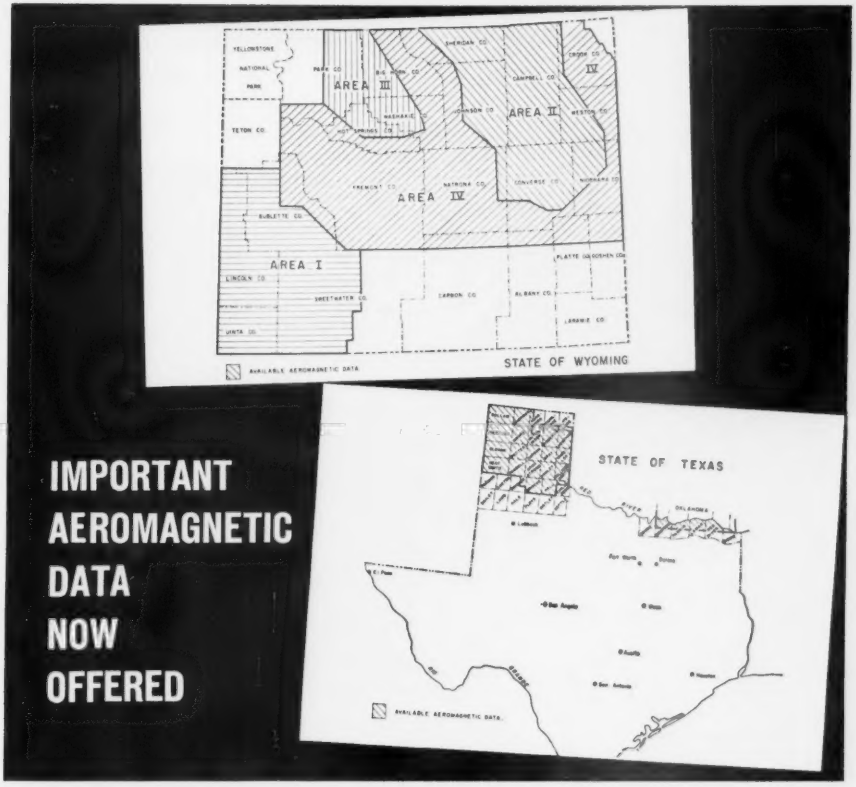

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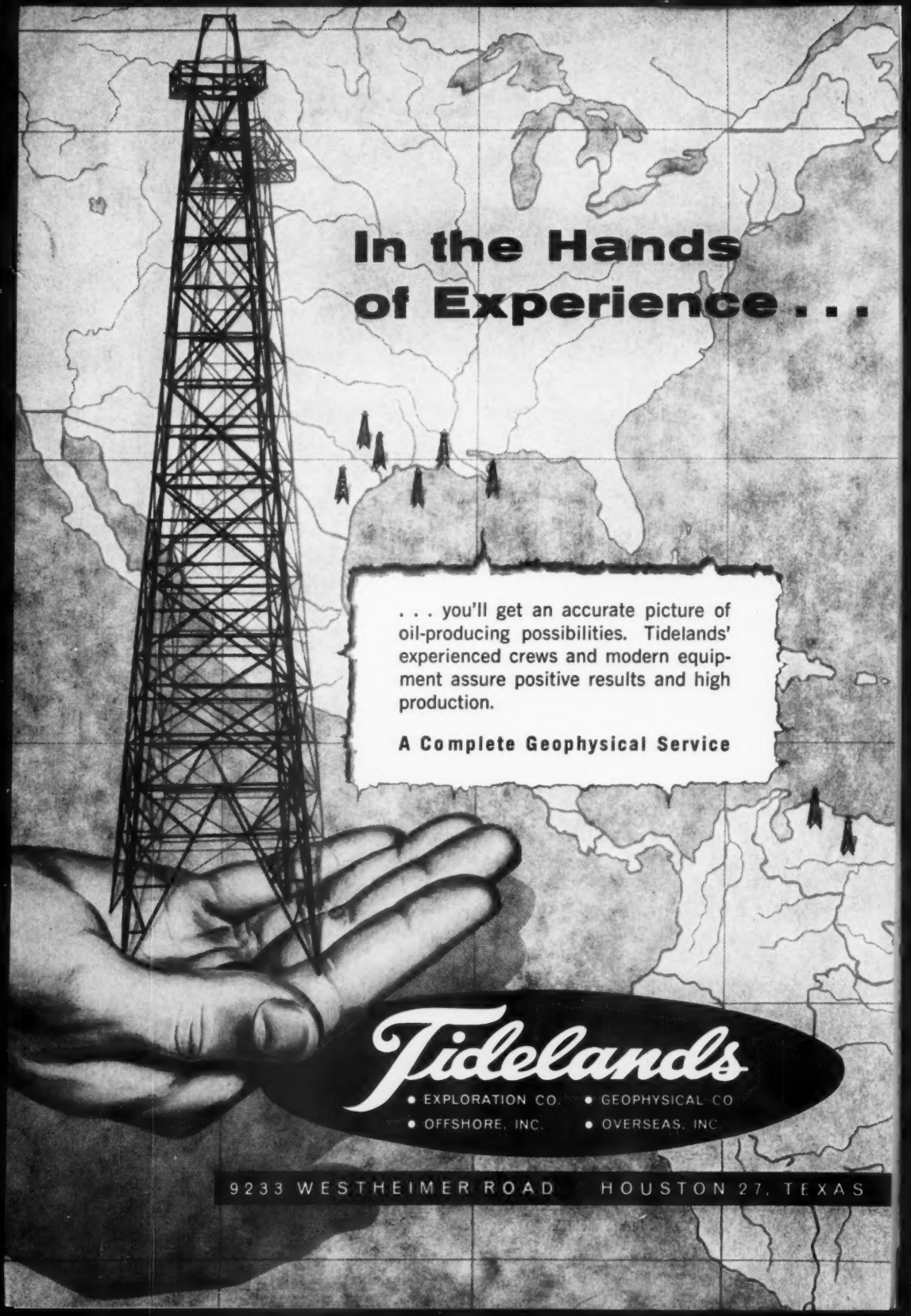
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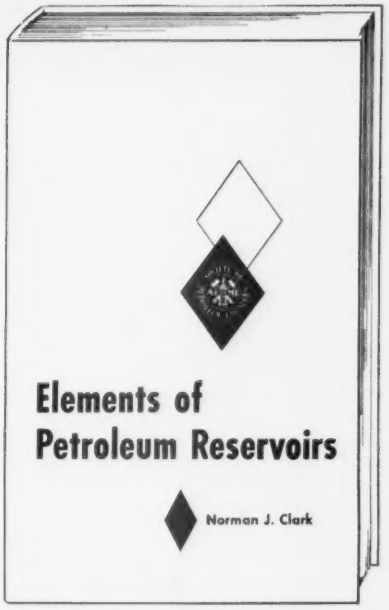

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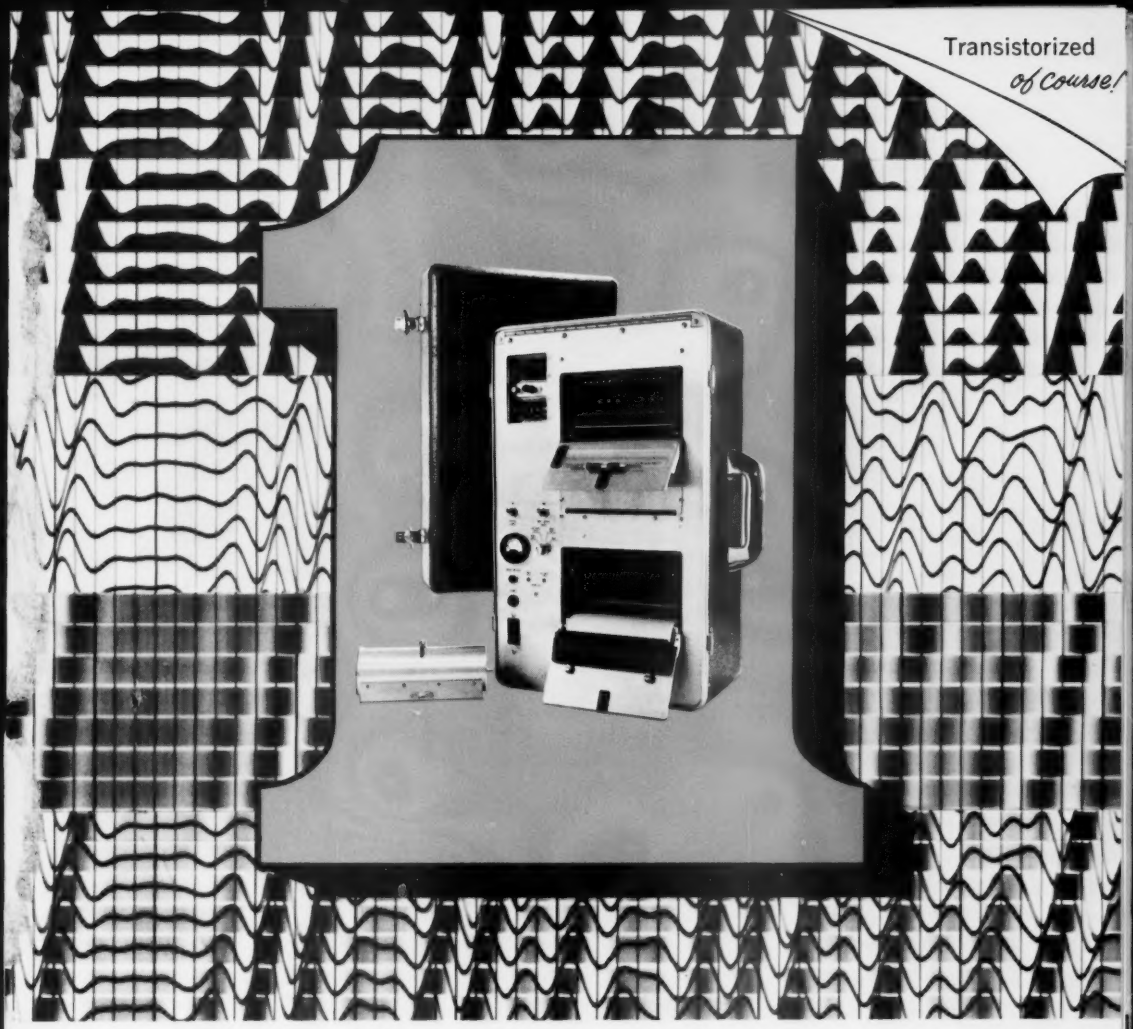

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Frequency response: 1 cps to 300 cps within 1 db; 3 db down at 500 cps

Signal-to-noise ratio: 60 db (rms), 1 to 500 cps with noise cancelling.
54 db (rms) 20 to 200 cps without noise cancelling.
(Peak-to-peak noise averages 6-10 db higher than rms noise)

Harmonic distortion: Less than 1%

Crossfeed: Below noise level of recording system

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Power requirement:

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Record	2 amp.	7 amp.
Playback	1.5 amp.	6.5 amp.

12 volts D.C.

Dimensions: MR-20 Recorder—8¼"W x 24½"H x 15"D
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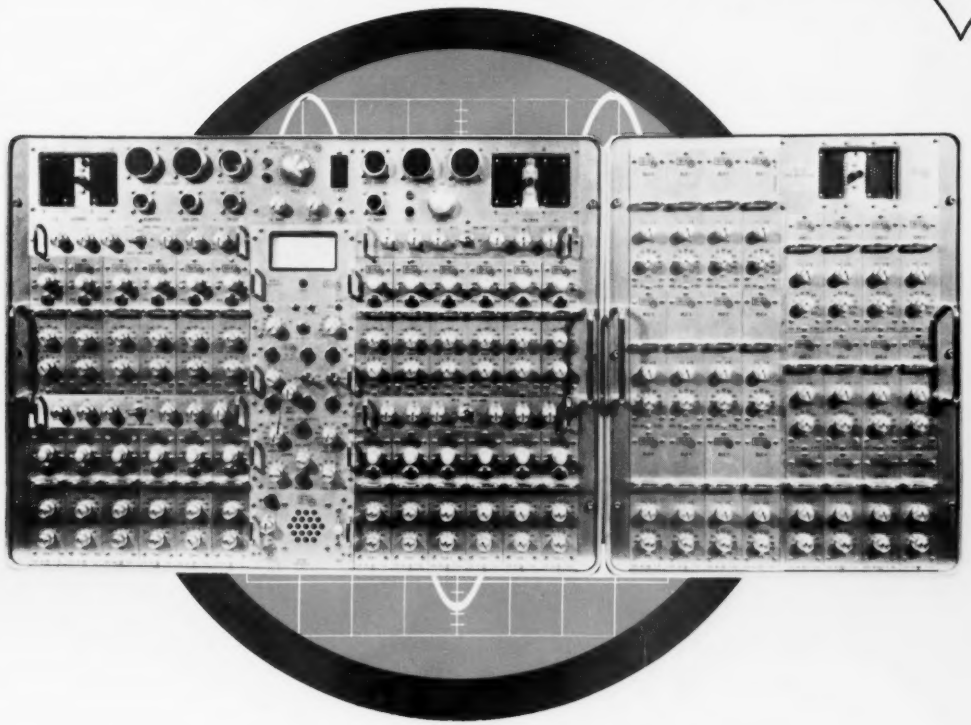

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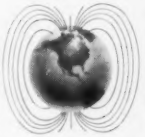

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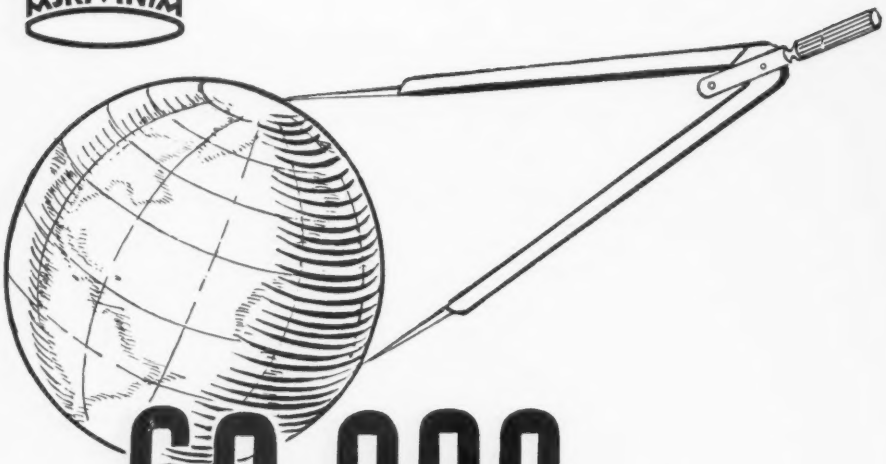

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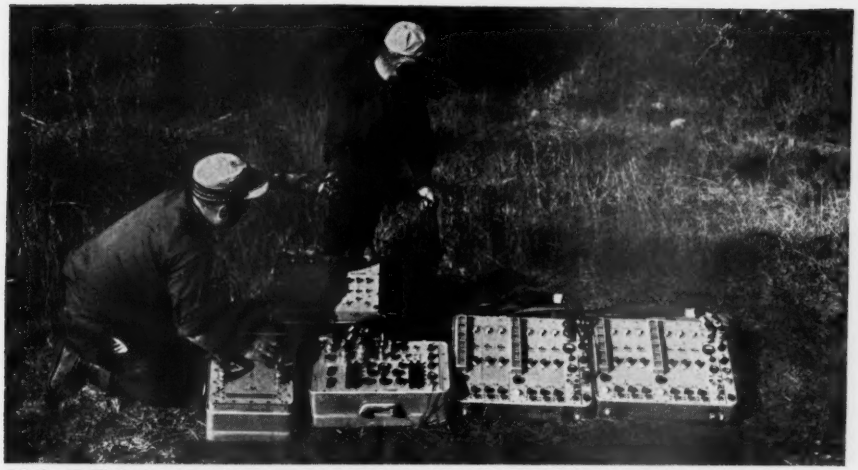

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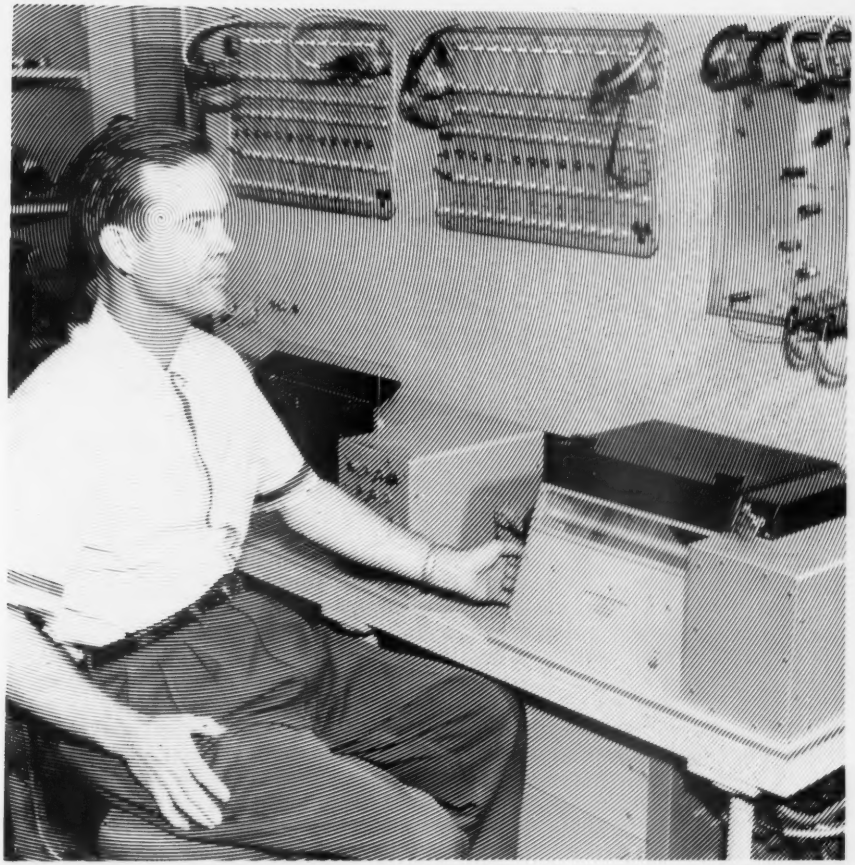

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Petty's research-development laboratories work constantly to develop and improve geophysical techniques. Conception of such advanced techniques as Petty's patented* horizontal stacking process is not enough. Practical implementation of the diverse data handling procedures is also necessary. Accuracy and speed are keynotes of the data processing system developed by Petty to afford economical applications of this technique. From idea to practical application, a method is no better than the thought and attention to detail applied to it. For information write to:

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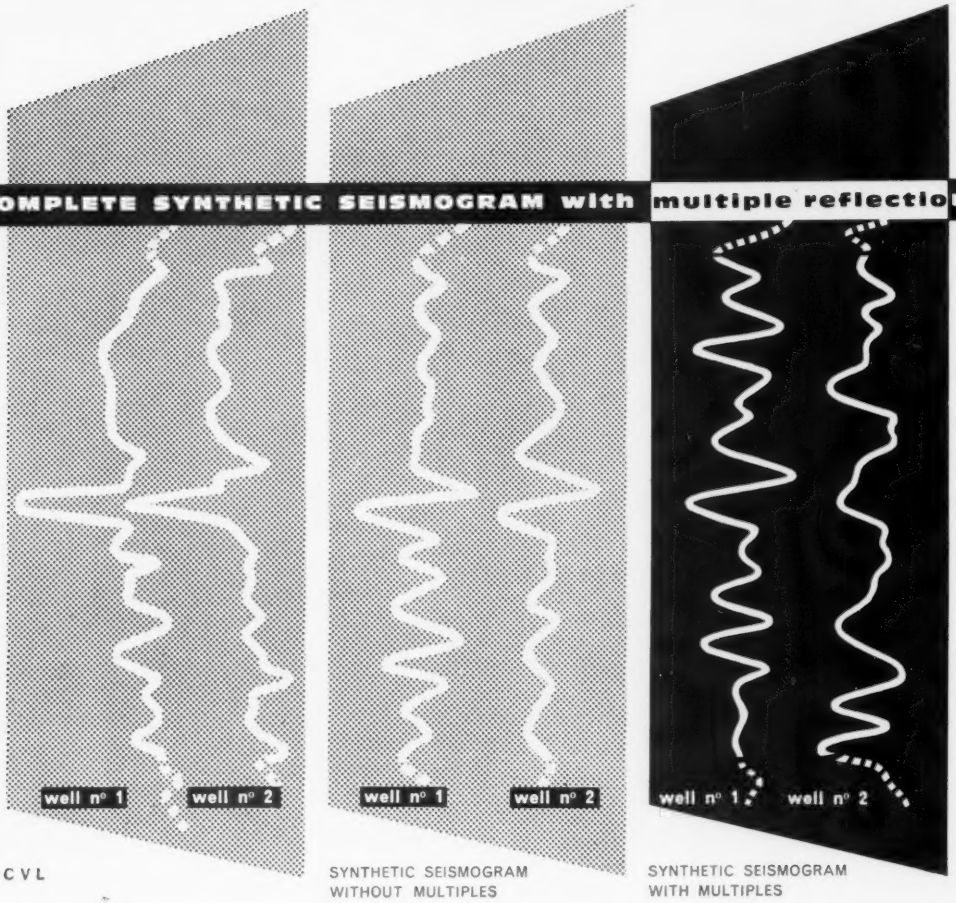
*U.S. Patent No. 2,732,906

A NEW METHOD OF IMPROVING THE PRESENTATION AND THE INTERPRETATION OF SEISMIC RECORDS

THE COMPLETE SYNTHETIC SEISMOGRAM with multiple reflections



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SYNTHETIC SEISMOGRAM WITH MULTIPLES

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The synthetic seismograms make it possible to ascertain the existence and the quality of the horizons which may be used as good markers

The synthetic seismogram leads to improvements of the field techniques: automatic gain control and filtering

The synthetic seismograms are conducive to a more complete and more acurate interpretation

Using the synthetic seismogram your past and present surveys can attain their full value

The cost of a synthetic seismogram with multiple reflections varies with the depth logged : 20 to 25 % of the cost of the logging operations proper

For a borehole of average depth, this cost is no higher than that of one kilometer of seismic profile

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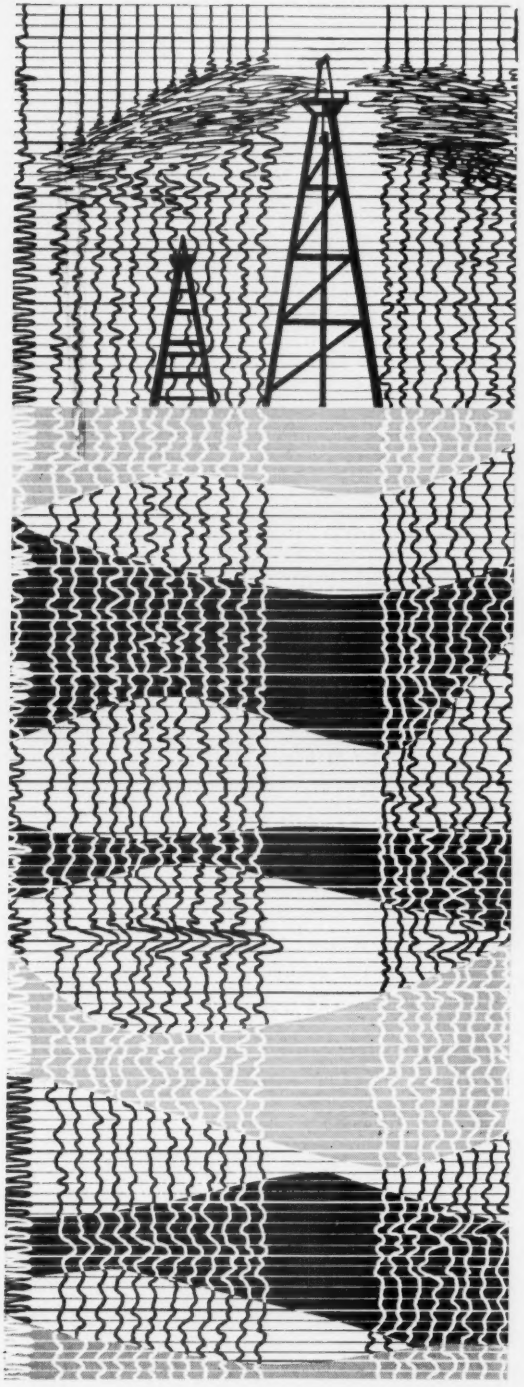

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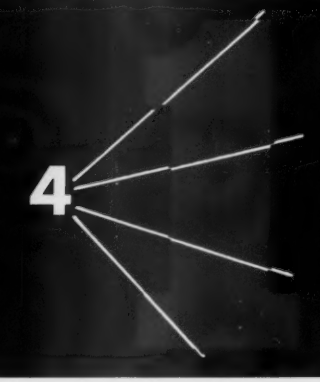

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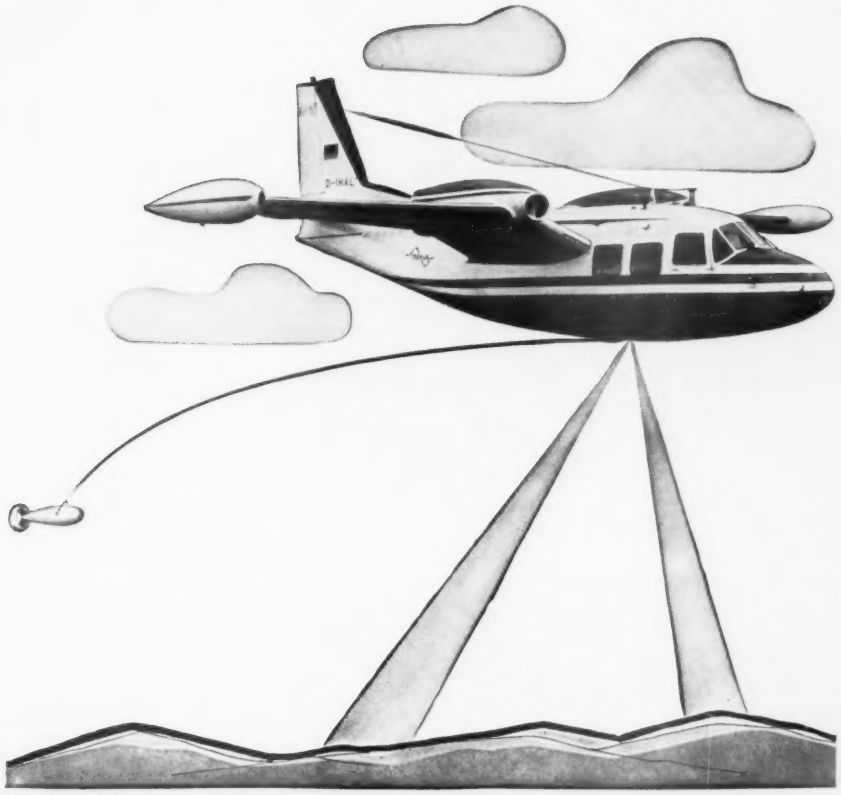

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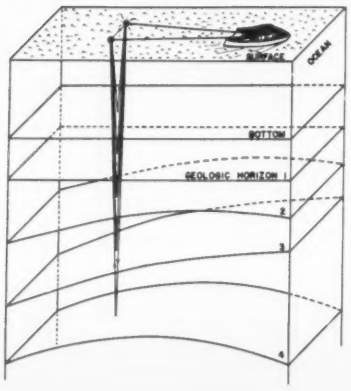

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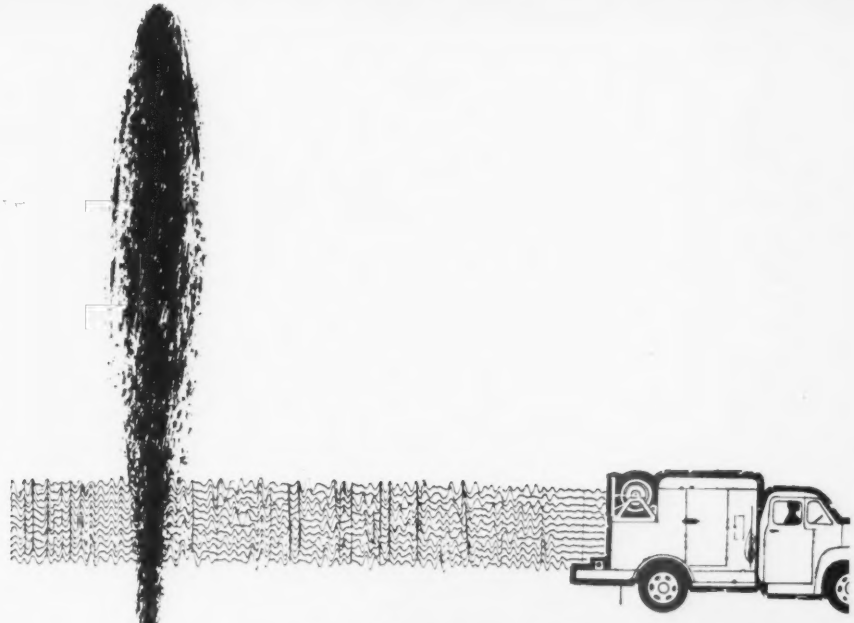

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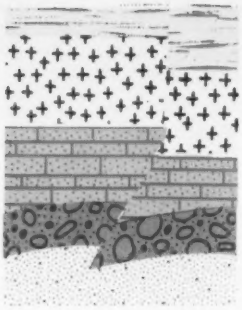

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The same high quality standards established for Electro-Tech products are maintained for EV Series products manufactured by subsidiaries in Annecy, France, and Calgary, Alberta, Canada.

EV-15 The new MODEL EV-15, Electro Tech's subminiature seismic detector, is design engineered to reduce weight and handling problems caused by the larger number of Geophones required in modern field survey techniques. The EV-15 weighs only 4 oz. Reliability, sensitivity and low cost are complimentary features of the EV-15, and are basic standards of all Electro-Tech seismic detector models. Designed in strict accordance with good engineering practices of stability and versatility, the EV-15 maintains an accuracy of $\pm$ 1½ cycles. These good engineering practices, a standard reflected in the quality of all EV Models, make it possible for Electro-Tech to unconditionally guarantee EV-15 Detectors for *two years against any defects, including high voltage damage.* All EV models are:

SENSITIVE

High signal-to-noise ratio. Parasitic spring resonances and metastability are absent. High electrical output, excellent frequency stability and good damping characteristics result in optimum sensitivity. Parasitic modes of vibration are absent within the seismic spectrum.

ECONOMICAL

Accuracy, reliability, low original cost, lightweight, miniature size, *easy replacement of parts in the field* combine to make the EV Series the most efficient and economical seismic detectors available.

RUGGED

Built to be abused, the solid construction design of inner parts assures stability in the toughest seismic surveys. Absolute two-spring construction provides coil stability, thereby minimizing horizontal response and increasing operational angle.

VERSATILE

Light weight and ease of handling in field operations, a wide selection of special purpose attachments and a variety of top and bottom attachments and a choice of brass or aluminum cases give maximum versatility to the EV Series detectors. Units are available for either marsh or land surveys.

EVS-2 MODEL EVS-2 Miniature Seismic Detector is the "Exploration Standard" of the geophysical industry. Field-tested, its reliability and sensitivity have been proven consistently during its 8 years use. As the basic design for the EV Series, EVS-2 construction has eliminated parasitic spring resonances and metastability. Available in frequencies from 14 to 30 cps with standard coil resistance of 215 ohms, its high elecrical output assures high signal-to-noise ratio.

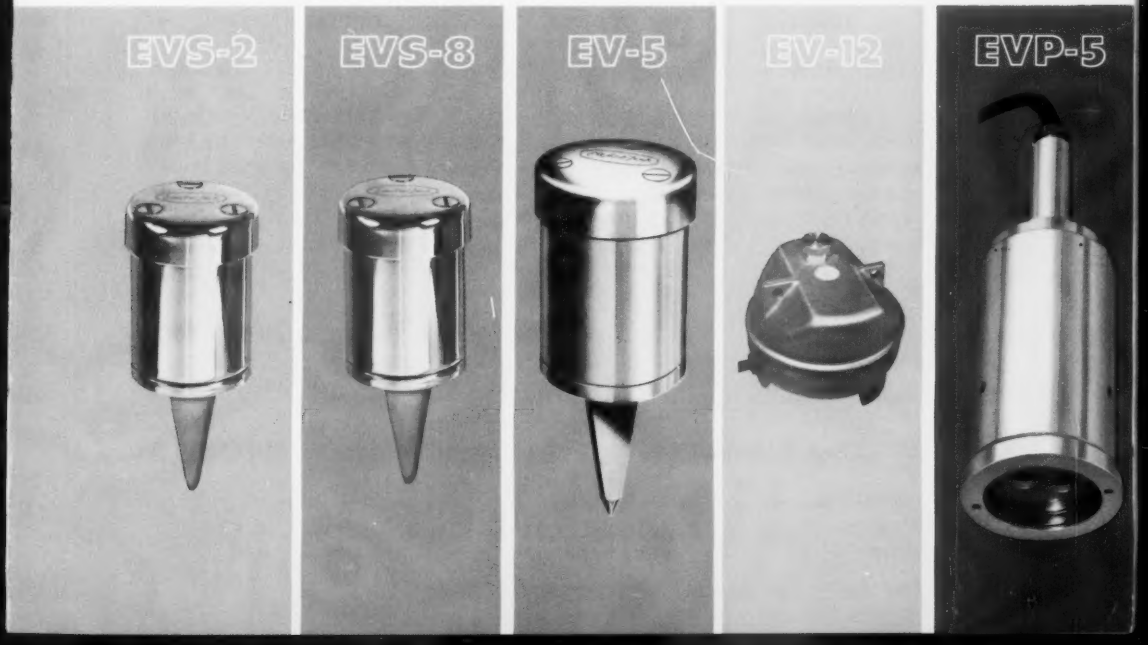
EVS-8 MODEL EVS-8 Miniature Seismic Detector is a 4.5 cps version of the EVS-2. This detector has excellent application in reflection and refraction surveys. Available in brass or aluminum cases with various marsh and land attachments.

EV-5 MODEL EV-5 Seismic Detector is a larger version of the EVS-2. It exhibits unusually high sensitivity and has excellent damping characteristics. EV-5 can be adapted to pattern operations. Available in brass or aluminum cases and accessories.

EV-12 MODEL EV-12 is the first truly field worthy very low frequency detector. Spring supported beam suspension requires beam pivot be highly flexible yet rugged enough for field handling. EV-12 employs a moving mass (magnet) stationary coil pickoff. This instrument's compactness, reliability and low price make it practical to use multiple detector patterns to increase signal/noise ratios. Standard coil impedance 500 ohms; 4000 ohm coil available upon request.

Model EV-5-4 is the 7.5 cps Model of the EV-5. Special impedances are available on order.

EVP-5 EVP-5 is a diaphragm actuated crystal pressure detector with integral impedance matching transformer and damping resistor. High sensitivity eliminates need for pre-amplification. Built-in balloon compensator maintains uniform sensitivity for water depths to 150 feet. No additional high-cut filters needed. Brass construction.



SPECIFICATIONS OF THE EV SERIES are the result of instrumentation engineering designed to provide the best equipment possible for practical field survey techniques.

FEATURES EV SERIES	EVS-2	EVS-8	EV-5	EV-12	EV-15	EVP-5
ELECTRICAL						
OUTPUT V/I/S (Open Circuit)	0.58 14 cps 215 ohms	0.6 4.5 cps 215 ohms	0.66 14 cps 220 ohms	0.9 1 cps 500 ohms	0.46 14 cps 215 ohms	0.49 7.5 cps 500 ohms
COIL (ohm) RESISTANCE	215 (125-1000)	215 (125-1000)	215 (125-1000)	500 (500-4000)	215 (125-1000)	500
FREQUENCIES cps.	14-30	4.5	14-30	1.0	14-30	7.5
PHYSICAL						
DIMENSIONS (H. x D.)	1¾ x 1⅝	1¾ x 1⅝	1¾ x 1⅝	3½ x 4½	1⅜ x 1	7 5/16 x 2 7/16
STUD	½ x 20	½ x 20	½ x 20	—	⅜ x 24	—
CONSTRUCTION*	A/B	A/B	A/B	A	CS	B
WEIGHT-Land **Marsh**	9.5 oz 13 oz.	9.5 oz. 13 oz.	2 lbs. 2½ lbs.	3 lbs. 3 lbs.	4 oz. —	3 lbs. 3 lbs.

* A-Aluminum; B-Brass; CS-Cadmium Plated Steel
** Weights are for Aluminum Cases, except EV-15 (cadmium plated steel) and EVP-5 (brass)

GEOPHONE ATTACHMENTS are available in full range of sizes. Bottom attachments include disc, tripod, spikes and cone bases. Special Purpose Attachments are Cable Entry Protector; swivel ring and straps and wire loops for stringing detectors on hangers. Top attachments include Moisture Prevention Caps; Water proof "Snap-On" Connectors; Marsh Shanks; Polarized Marsh Shank with "Snap-On" connector feature; anchor strap; Inline Tandem Cable Connector; "T" Tandem Cable Connector.

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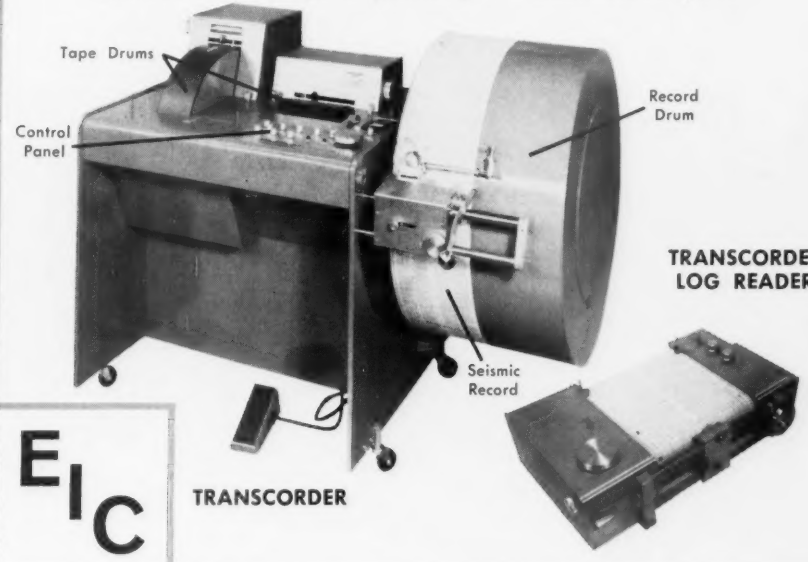

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The Transcorder, EIC's new data-transcribing device, transcribes seismic data onto any standard geophysical tape from paper records, from other sizes of magnetic tape, or, using the Transcorder Log Reader, from well logs. A reproduction of a seismic trace being transcribed can be produced simultaneously for checking purposes.

Magnetic tapes produced by the Transcorder can be processed by playback systems that permit mixing, selective filtering, correcting for moveout, weathering, and elevation, and plotting cross sections by the conventional trace, variable-area, or variable-density methods.

The paper record being transcribed onto tape is mounted on a large revolving drum. The magnetic tape is mounted on another drum that is servo-driven at an infinitely variable rate. The Transcorder will accurately transcribe paper records recorded at speeds ranging from 7.5 to 15 ips. The magnetic recordings produced are accurate within $\pm 1\frac{1}{2}$ ms of the original record at all times.

The Transcorder operator guides the tracking head as the record-carrying drum revolves. (Unskilled office personnel can operate the Transcorder.) The traces are individually transcribed to magnetic tape.

The Transcorder Log Reader, an accessory, permits transcribing well logging data onto magnetic tape in the same manner as conventional seismograms. The resulting tapes can be then converted to cross sections by seismic data reduction systems.

Write or wire EIC for detailed specifications

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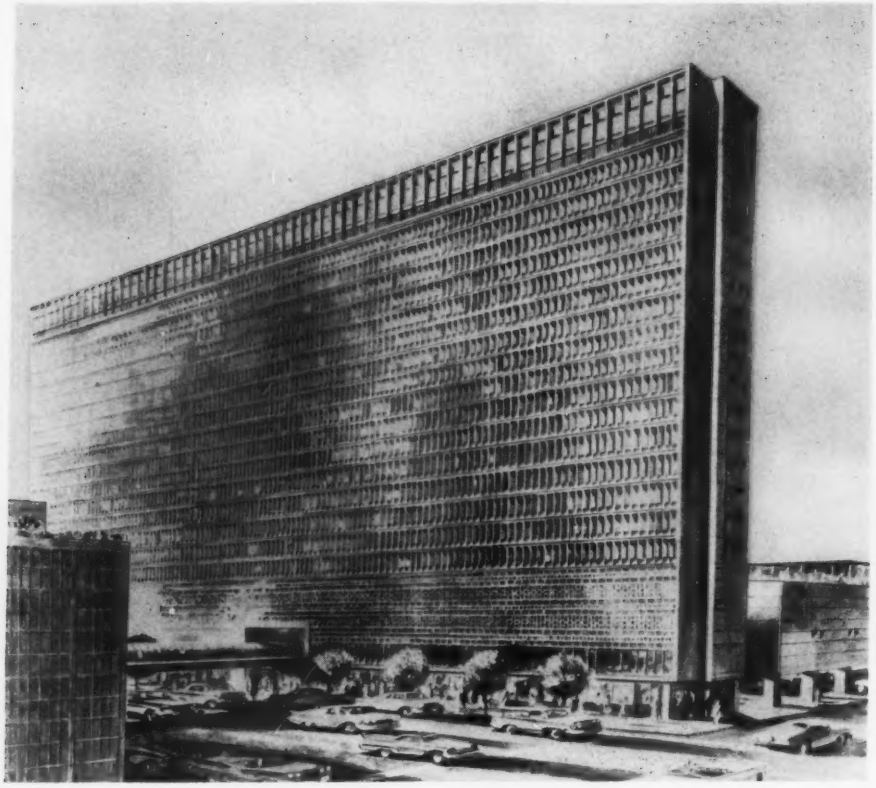

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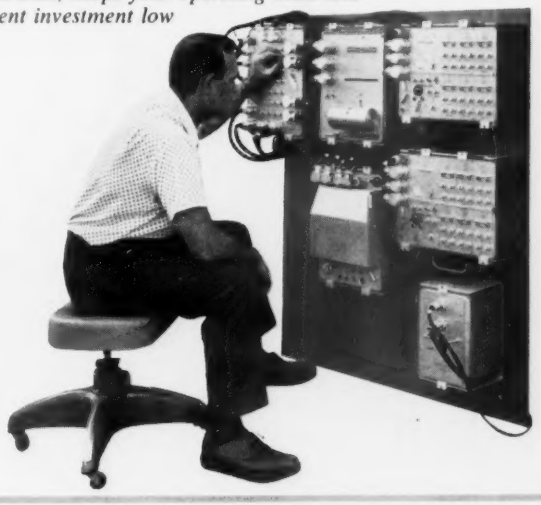
this complete 24-channel seismic system produces high-quality tape-recorded data, keeps your operating costs and field-equipment investment low



EIC

Although it weighs only 157 lb, the PSS-50 is a complete seismic system, consisting of two 12-channel seismic amplifiers, a tape-transport unit, a translator unit, and a master control unit.

The system's low cost and weight were gained by designing it to utilize fully the capabilities of magnetic tape and by including only needed filtering and display capabilities. The result is a truly portable system that performs superbly.

The seismic amplifiers have a flat frequency response from 8 to 250 cps. Filtering is provided by a separate plug-in unit. Filtering available includes 12 to 24 db per octave slopes, with 20, 30, and 40 cps cutoff points. Cutoff frequencies can easily be changed by plug-in capacitance boards.

A master control unit provides uphole level control, leakage and continuity testing, trip indicator and manual control, trip sensitivity control, master suppression control, avc on-off control, and a test oscillator. Timing accuracy is ±1 ms.

The tape transport unit has a full 28-channel magnetic recorder, featuring standard EIC door-mounted recording heads. Heads can be interchanged without disassembling the tape transport. Recording heads have excellent low-frequency and transient response. The accurate, reliable drive system uses a hysteresis synchronous motor and a spur-gear transmission.

The translator unit has a playback amplifier with additional avc and filtering control. Traces are displayed on electrosensitive paper by a rectilinear pen writer. Each data channel is played out sequentially and automatically. Timing is provided by preprinted timing lines, with the 100 cps timing trace from the tape played out as a check. Two paper speeds are available, one for a full-length record, the other for expanding the first third of the record (covering the first-break region) over the full paper length. Accuracy from trace to trace is ±1 ms.

Power required for the PSS-50 is 12 v at 8 a during standby and 18 a while recording.

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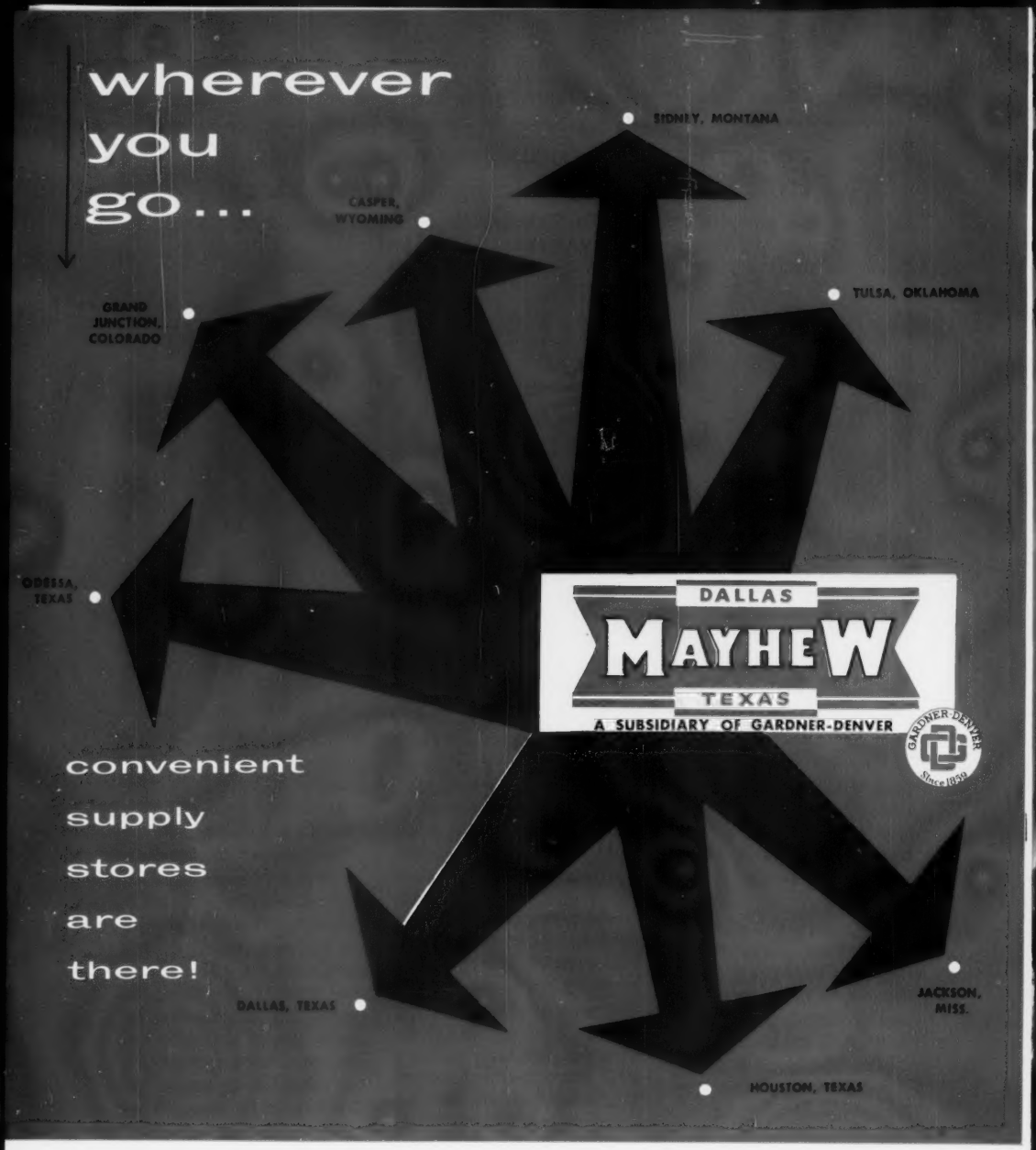

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Standard of the Industry

this versatile playback system simplifies your toughest data analysis problems

using EIC's central office seismic data reduction system, you can easily apply precise corrections to field-recorded tapes, use mixing, compositing, or stacking, select the most effective presentation modes

Field Tape Playback Unit

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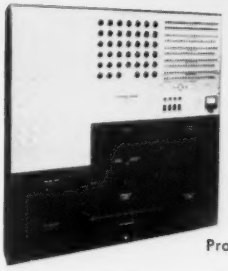

Programming Assembly

C-850

EIC

When you own the C-850, you have the most flexible single system available for sequential playback of magnetic tapes. It lets you make maximum static corrections of ±100 ms and dynamic corrections up to 400 ms (at a maximum rate of 500 ms per sec). Timing accuracy is ±1 ms. Any geophone spread length or arrangement can be handled.

During playback, time-corrected seismic data are plotted simultaneously to photographic cross sections. You can choose conventional - trace, variable - area, or variable - density cross sections, or any two of these three. Seismic data can be referenced to any desired datum plane on the cross-section plots. As many as 864 traces can be recorded on a single cross section, which may be as large as 72 x 72 in.

Corrected data are re-recorded during playback for future evaluation. As many as 12 channels of re-recorded tape can be played back for mixing, compositing, or stacking to cross-section plots.

The C-850 can be supplied with any standard-size tape transport. It handles up to 50 seismic and information channels at tape speeds of 7.5, 3.75, or 3.6 ips. It can reproduce direct, FM, or PWM recordings. Re-recording is by FM. Cross-section plotting speed is from 7.5 to 10 ips.

Distortion on FM is less than 1%, on direct magnetic recording, less than 2.5%. Frequency response is from 5 to 500 cps. Signal-to-noise ratio is 52 db (rms-rms) on direct recording, 46 db (rms-rms) on FM.

Such standard EIC design features as door-mounted recording heads and 400-cps hysteresis synchronous motors make the C-850 reliable, easy to maintain, and relatively inexpensive.

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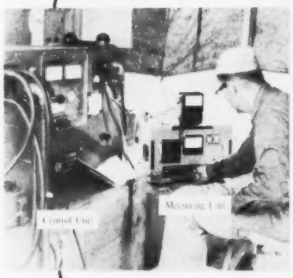
Hunting is the first to offer contract services with deep-penetration pulse-type Induced Polarization equipment. This equipment has been successfully used in exploration for disseminated sulphide ores which do not respond to other electrical methods and offers particular advantage in interpretation of responses in areas of low-resistivity overburden and stratified rocks.



Salient features of the equipment include:

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- Depth of penetration of more than 2,000 feet
- Effective penetration of low-resistivity overburden
- D. C. resistivity recorded along with overvoltage reading
- High sensitivity (± 10 per cent of background)
- Rapid operation (e.g. 1 mile per day at simultaneous spacings of 400 and 800 feet)
- Accurate positioning of source of polarization
- Use of any electrode array through suppression of interline coupling
- Console may be located in any terrain accessible by four wheel drive vehicle
- Electrodes may be placed up to 13,000 feet from console

Considerable operational experience with this unit has been gained in Canada and the United States, particularly in Southwestern U.S.A.

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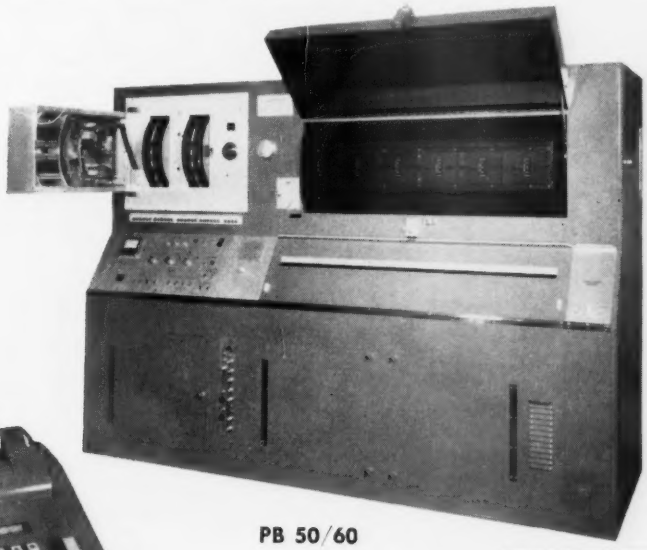
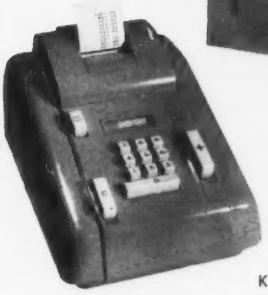


PB 50/60



Keyboard Input Unit

EIC

The PB-50/60 sequential playback system was engineered and built to give reliable service under adverse field conditions. Its single-console construction makes it easy to move from one location to another, and its rugged, simple construction makes it easy to maintain. Despite its low cost, the PB-50/60 gives you great flexibility of operation and ±1 ms accuracy.

Normal moveout corrections up to 240 ms are available at a maximum rate of 500 ms per sec. Maximum weathering and elevations corrections of ±100 ms can be applied. All corrections are inserted easily and rapidly by a keyboard input unit.

Timing lines on cross sections are recorded directly from field timing signals, giving you accurate trace plots that are in true relation to each other and to record time. Seismic information can be accurately referenced to any desired datum plane. Either conventional-trace or variable-density cross sections are plotted photographically on 24 x 72-in. tape or film. This system can be supplied with any standard-size tape transport.

Modifications of the basic PB-50/60 can be supplied to meet specific requirements.

Write or wire EIC for detailed specifications

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fidelity, timing accuracy mark this direct recording magnetic tape system

this direct recording magnetic tape system updates seismic systems to provide high-quality tape-recorded data for analysis in seismic data reduction systems

DR-50

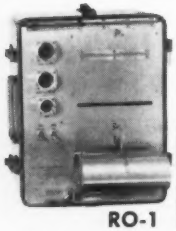
The DR-50 magnetic recording systems produced by EIC record up to 50 seismic and information channels. Record - reproduce heads have excellent low-frequency and transient response. They are mounted on the access door so that they can be inspected, adjusted, or replaced without disturbing the tape transport.

The neatly packaged plug-in amplifiers used as dual-purpose record and reproduce units provide proper playback compensation down to 5 cps.

The DR-50 features timing accuracy of ±1 ms, with trace - to - trace accuracy of ±0.5 ms. Frequency response is from 10 to 500 cps. Signal-to-noise ratio is 52 db (rms). Total harmonic distortion is 2.5%. The DR-50 is driven by EIC's reliable 400-cycle synchronous motor.

The DR-50 is available either with or without a buffer unit. The buffer is used when the seismic amplifier cannot drive the recording heads directly or when a superior signal-to-noise ratio is needed for field playback. EIC engineers are experienced at integrating systems with existing amplifiers and can provide turnkey installation of DR-50 systems.

you get dependable field performance from this rugged recording oscillograph



RO-1

The RO-1 recording oscillograph photographically records up to 28 seismic data traces on 6-in. paper or film. A 400 cps hysteresis synchronous motor provides uniform paper speeds from 3 to 45 ips. Speeds are selected by interchanging easily replaceable drive gears. Precise time correlation is insured by sharply defined timing lines. The RO-1 has 28 pencil-type galvanometers that are available in natural frequencies from 125 to 500 cps. Both galvanometers and front-surfaced mirrors can be adjusted readily in the field. Because the RO-1 produces very little noise in the battery circuit, a single battery can power both the camera and the seismic amplifier. This simplifies battery-charging problems and makes the RO-1 especially suitable for truck mounting.

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cut uphole shooting time and costs with this precision interval timer

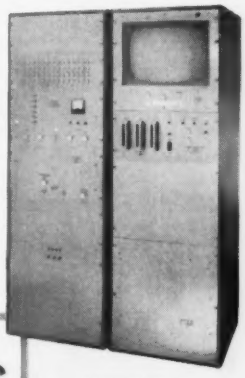
you can obtain weathering and subweathering velocities accurately and efficiently with this interval timer, without using costly seismic recording systems

GT-1

EIC's GT-1 geophysical interval timer is a precision digital readout instrument that simplifies uphole shooting operations. It provides an immediate visual display of the time interval from shot detonation to the initial seismic wave received by an uphole geophone. Accuracy is ±0.5 ms. A maximum time interval of 255.75 ms can be recorded.

The GT-1 is completely transistorized. It is powered by self-contained dry-cell batteries. The unit's total weight, including batteries, is only 17 lb. Its aluminum carrying case is 16 x 9 x 7¾ in.

now you see results of filtering, stacking, mixing without waiting for cross sections



MSS-100

The MSS-100, a remarkable new multitrace electrostatic storage system developed by EIC, lets you store up to 28 seismic data traces for visual readout on a 17-inch, TV-type, video monitor. This advance in the art of handling seismic data can help you cut the cost of analyzing geophysical data.

The MSS-100 stores data from tape-recorded seismic traces in a special storage tube and displays them continuously on the monitoring tube. Traces can be displayed for as long as 20 minutes without appreciable deterioration. They can be erased instantly to permit storing new data.

Vertical timing lines can be displayed on the video monitor at 1/100-second intervals, with 1/10-second lines accentuated. Either the 1/100- or 1/10-second lines can be omitted if desired.

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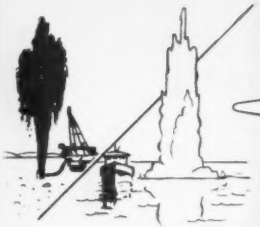

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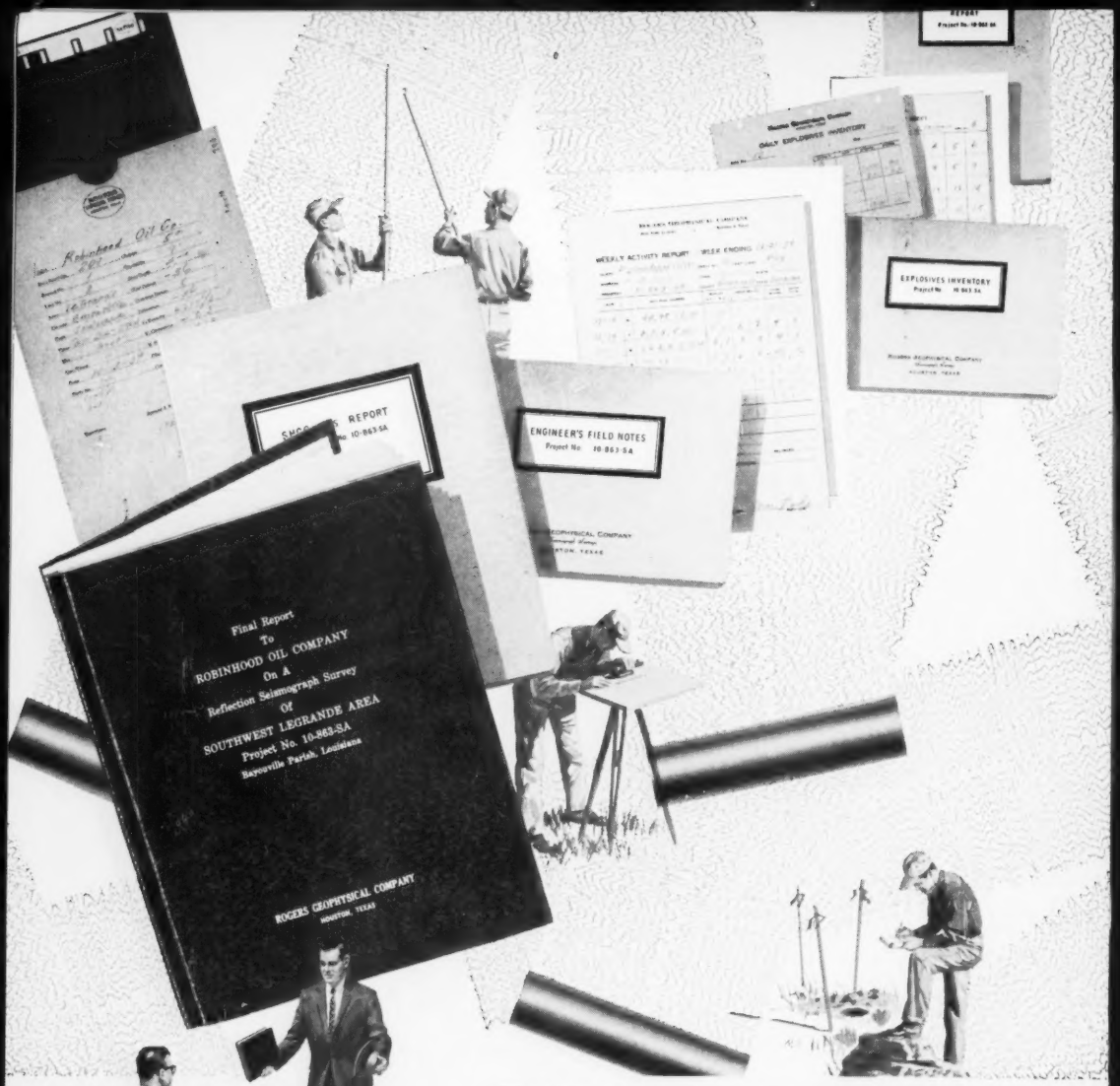

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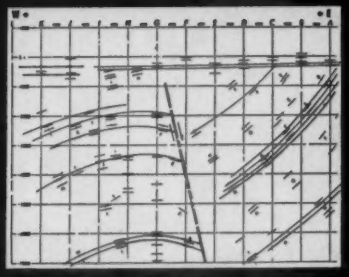

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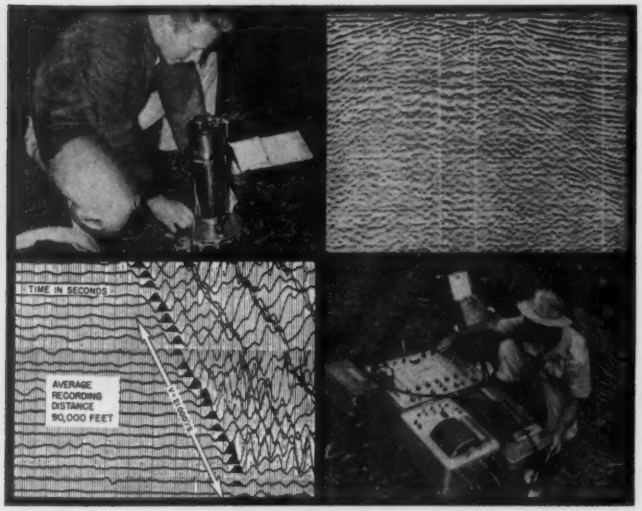

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